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**The Aha! Experience**  
**of**  
**Spatial Reorientation**

by  
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I, Efrosini Charalambous confirm that the work presented in this thesis is my own.  
Where information has been derived from other sources, I confirm that this has been  
indicated in the thesis.

Signature.....

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## **Abstract**

The experience of spatial re-orientation is investigated as an instance of the well-known phenomenon of the Aha! moment. The research question is: What are the visuospatial conditions that are most likely to trigger the spatial Aha! experience? The literature suggests that spatial re-orientation relies mainly on the geometry of the environment and a visibility graph analysis is used to quantify the visuospatial information. Theories from environmental psychology point towards two hypotheses. The Aha! experience may be triggered by a change in the amount of visual information, described by the isovist properties of area and revelation, or by a change in the complexity of the visual information associated with the isovist properties of clustering coefficient and visual control. Data from participants' exploratory behaviour and EEG recordings are collected during wayfinding in virtual reality urban environments. Two types of events are of interest here: (a) sudden changes of the visuospatial information preceding subjects' response to investigate changes in EEG power; and (b) participants brain dynamics (Aha! effect) just before the response to examine differences in isovist values at this location. Research on insights, time-frequency analysis of the P3 component and findings from navigation and orientation studies suggest that the spatial Aha! experience may be reflected by: a parietal alpha power decrease associated with the switch of the representation and a frontocentral theta increase indexing spatial processing during decision-making. Single-trial time-frequency analysis is used to classify trials into two conditions based on the alpha/theta power differences between a 3s time-period before participants' response and a time-period of equal duration before that. Behavioural results show that participants are more likely to respond at locations with low values of clustering coefficient and high values of visual control. The EEG analysis suggests that the alpha decrease/theta increase condition occurs at locations with significantly lower values of clustering coefficient and higher values of visual control. Small and large decreases in clustering coefficient, just before the response, are associated with significant differences in delta/theta power. The values of area and revelation do not show significant differences. Both behavioural and EEG results suggest that the Aha! experience of re-orientation is more likely to be triggered by a change in the complexity of the visual-spatial environment rather than a change in the amount, as measured by the relevant isovist properties.

## Impact Statement

This is the first study that analyses the EEG signal and examines the brain dynamics of single trials in direct relation to quantifiable visuospatial properties. The findings are based on an ecologically valid experimental paradigm that uses a real-world scenario and takes into consideration experiential, behavioural, neural and context-based events. Ecologically valid experiments permit the collection of behavioural and neural data during interaction with realistic environments where participants can have a real-world experience, move freely within an environment and respond to the task in a natural and unforced way.

The thesis contributes to creating intellectual bridges between the fields of the built environment and cognitive science. On the one hand, it provides evidence that supports the view that the correlations, observed in space syntax research, between aggregate flows of movement and syntactic variables are due to cognitive factors operating at the level of the individual. The findings suggest isovist measures are associated with differences in individuals' brain dynamics. On the other hand, neurophysiological studies on navigation in real-world settings require a methodological approach that includes the study of human spatial experience as a response to environmental properties of the spatial context. The findings from this PhD project suggest that environmental modelling techniques can be used to control experimental conditions and time-lock the EEG analysis to specific environmental changes. The results and methodology used in this paradigm open new directions for further research and expand the space of possible research questions. They provide the ground upon which new hypotheses can be structured and the means to control experimental conditions, based on quantitative environmental modelling in innovative virtual reality neurophysiological studies.

Some parts of the research have already been presented in international conferences related to the fields of spatial cognition and/or the built environment, such as the *KogWis 2016, Space for Cognition* conference in Bremen and the *11 Space Syntax Symposium* in Lisbon. Articles that discuss the findings and methodology of this thesis will be published in at least three high-impact international peer-reviewed journals such as *Environment and Planning B*, *Journal of experimental psychology*.

*Learning, memory, and cognition* and *Frontiers in Psychology*. Research results will be presented at national and international conferences. Oral presentations will include the *third iNAV Symposium* in 2020 and the next *Spatial Cognition conference* (XII). The results of the project, published in peer-reviewed journals in open access journals (i.e. UCL Discovery) and presented at international conferences, will be disseminated across the research community making them available for further study and direct comparison with other new data.

The behavioural and electrophysiological results of this study reveal a strong association between the Aha! experience of reorientation and the change in the complexity of the environmental input, as measured by the relevant isovist properties. These findings can be useful when designing environments for older populations that may often have decreased orientation skills (e.g. retirement developments). The methodology may contribute to evidence-based design relative to the impact of a certain environment on peoples' well-being and mental health, before proceeding to construction and post-occupancy evaluations. Neurophysiological evidence regarding the subjective experience of the built environment can be also used to influence policymakers on prioritising in human-centre design.

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## **CHAPTER 1    Introduction**

## 1.1 Introduction to the Topic

The shift of focus from the virtual to the neural within the field of architecture and the built environment is accompanied by a growing interest towards the knowledge offered by the cognitive sciences and studies that explore the direct lived experience of having a body capable of sensing and moving within its environmental context. Contemplating the movement of bodies in space, the inter-relation of the senses and the notions of affect and lived experiential events, Brian Massumi raises the following question: “What ‘environmental’ forces, for the emergence of new form [of lived experience], might we find if we take a new look at the physiology of the brain?” (Massumi, 2006). He reflects on this transition from the virtual to the neural and suggests that the impact of cognitive neuroscience changes the role of architects, from designing spaces for practical function to '*becoming experienced engineers*' focusing on ‘the creative emergence of new forms of lived experience’ (Massumi, 2006). A direction towards “a principled consideration of embodiment as lived experience” is also central in Varela’s work (Varela, 1996). He highlights how the “study of mental phenomena is always that of an experiencing person” and argues for a circular movement between the cognitive sciences and a disciplined study of the direct human experience (ibid.).

The pursuit of empirical neurophysiological data associated with the embodied human mind, situated within the built environment, necessitates a disciplined account of the human spatial experience. For the fusion process of cognitive neuroscience and a disciplined approach to human experience, Francisco Varela proposes the field of *Neurophenomenology* (Varela, 1996). Varela claims this can be achieved through the conscious gesture of *phenomenological reduction* (PhR)<sup>1</sup>, which entails “the re-discovery of the primacy of human experience and its direct, lived quality” (ibid.). Such a gesture may provide also a fertile ground between the disciplines dealing with the design of spatial relations and the sciences of the mind. Research on embodied cognition, focusing on wayfinding and navigation under real-world conditions,

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<sup>1</sup> The base of PhR can be decomposed into four intertwined moments: Attitude, Intimacy, Description and Training. The Attitude of *reduction*, “a tolerance concerning the suspension of conclusions”, allows the aspect of *intuition* to unfold, the ‘aha’ experience, as a new stage of understanding. The next component is to translate the gain in intuitive evidence into communicable items that he calls *invariants*. The fourth aspect is about *stability*. The sustained training in a method entails transformation and can make previously unavailable aspects of experience accessible (Varela 1996).

requires an equally weighted consideration of the spatial context, the neural firings and the direct lived quality of the human experience.

This enquiry, however, requires to recognise and isolate specific phenomena (case studies) within the flux of the experience in order to study their neural and experiential side. A possible direction is to identify moments of transition from one experiential state to another. A quite promising case study is that of a transition from a state of not-knowing to a state of knowing. This transition may have different degrees of suddenness or un-predictability. It can be gradual and rely on step-by-step associations between objects or events or it can be sudden, unexpected and surprising. The second case is not an uncommon experience and is often found, for instance, in insightful problem-solving situations. It is the specific phenomenon of the Aha! moment.

The subjective experience of the ‘Aha! moment’ or ‘Eureka!’ is a fascinating example of a direct lived experience and it has been of much interest to many scholars. It is of great interest because it is related to new discoveries, the emergence of new solutions and artistic creations. It is a manifestation of the moment that a thought or mental object becomes available to the conscious mind. It is interesting because it changes the course of action; it is an act of creation. This creative act has “a revolutionary or destructive side” (Koestler, 1964, p.659); it restructures the mental organisation of established habits and ways of thinking as opposed to associative thinking which relies on habit. This creative act “could be described as the highest form of learning because of the high improbability (or anti-chance probability) of the solution” (Koestler, 1964, p.657).

But is there an instance of this phenomenon that is more closely related to the direct experience of having a body capable of sensing and moving within its environmental context? Can we identify such a sudden transition from a state of not-knowing to a state of knowing within the context of wayfinding and navigation?

Reflecting on the spatial experience while navigating the streets of London, such moments can be found, for example, when one suddenly perceives a “connection” between two regions within a city's district which, until that moment, have only been

experienced separately. That is, when one experiences the spatial relation between two previously unrelated regions or when one gains insight into a possible new shortcut, then there is a sudden change in the mental spatial representation. But the most sudden transition we might experience is when we pass from a state of disorientation to a state of re-orientation, from a state of not-knowing where we are in space to a state of knowing. This is a common experience that people have when coming out of the tube. In this case, the gradual spatial updating of our position and heading is disrupted because we are teleported to a new location. Thus, when coming out of the tube in a relatively unfamiliar area we are often found in a state of not-knowing where we are and which direction we are heading in until the moment we suddenly realise, for example, that we are heading in the completely opposite direction.

The topic of this thesis is the spatial “Aha!” moment, an experience most people have whilst wayfinding in an unfamiliar environment and instantaneously transitioning from a state of being lost and disorientated to a state of being both situated and orientated with respect to their goal. This phenomenon is relatively underinvestigated within the field of wayfinding, especially in large-scale environments and during navigation in ecologically valid experimental settings. Investigating the conditions under which this phenomenon emerges during wayfinding may contribute to understanding where it is more likely to recover our position and heading in relation to the environment. It is also possible that the visuospatial cues that facilitate re-orientation are directly represented in memory (Kelly et al, 2013) and thus we can understand where we tend to anchor our allocentric representations. In addition, it may contribute to understanding how we explore relative unfamiliar environments, what drives this exploration and how we extract information from the chaotic environment: the actual built spatial configuration or even the abstract 'problem space'.

Therefore, the central research interest is in the experiential event of the spatial Aha! moment, its lived quality, the conditions that might trigger it and how these are manifested, as neural firings, as mental events in the recorded signal of brain activity. Then, the research question arises: *how, and when, are experiential events such as the Aha! moment triggered by the 'environmental forces' of the built environment?* In

the following sections, I will introduce in more detail the area, goals and methodological approach of this thesis and will try to provide the theoretical framework through which experiential events, mental events and context-events are examined. Finally, the last section of the chapter offers a brief introduction to the hypotheses of the thesis.

## **1.2 Area and Goals of Research**

The Aha! experience is a unique form of spontaneous understanding or one-shot learning. It is qualitatively different from analytical reasoning and depends on solutions that emerge through insights. The thesis is focused on this experiential event but in the context of navigation and wayfinding. Wayfinding can be approached as a kind of problem-solving situation that involves self-initiated movement in space to achieve a certain outcome, for example, to reach a goal or reward or enrich spatial knowledge through exploration. The analogy between wayfinding and the general notion of problem-solving seems to provide a fruitful theoretical tool, which enables the investigation of the specific mental events in real-world complex scenarios. The working hypothesis is that the experience of spatial re-orientation can be seen as an instance of this Aha! phenomenon. This idea finds support in early research on insightful problem solving, which suggests that the “reorientation of one’s thinking could be subserved by a similar hippocampal function to that of reorientation in navigation” (Luo & Niki, 2003).

The process of insightful problem solving is usually approached on the basis of its four salient features: mental impasses, perceptual restructuring, a deeper understanding of the problem, and an Aha! feeling of suddenness and correctness of the solution (Sandkuhler & Bhattacharya, 2008; Shen et al, 2013a), which results in a change in the course of action. In the case of sudden re-orientation, a similar pattern can be observed: the experience of mental impasses of disorientation, a perceptual restructuring of the spatial information, a deeper understanding of one's position and heading direction, and the Aha! experience that results in changing the course of action.

When the ‘sense of direction is no longer anchored to the external world’ one might have the experience of disorientation (Dudchenko, 2010, p.251). To gain re-orientation one must acquire a ‘deeper understanding’ of the current location and direction by anchoring the mental representation to ‘fixed elements’ of the immediate environment. The moment when individuals reorient within the built environment in regards to their location and heading direction after being lost, involves a sudden sense of spatial presence, a feeling of ‘knowing where one is’. Spatial presence can be defined as “a ‘gut’ feeling of being in a specific spatial context, and intuitively and **spontaneously** knowing where one is with respect to the immediate surround” (Riecke & von der Heyde, 2002, emphasis added). This then leads to the Aha! effect of recognizing where one is and then becoming aware of one’s actual heading.

A recent review of behavioural, electrophysiological, and neuroimaging studies suggests that environmental geometry is a predominant cue for re-orientation (Julian et al, 2018). Based on these findings and the working hypothesis of this thesis, the following research question is raised: *What are the visuospatial conditions that may engender the Aha moment of re-orientation?* Or in other words, *what kind of visuospatial cues provide us with enough information to orient ourselves when we are not sure of our location and heading direction?*

### 1.2.1 Sub-processes of re-orientation

The process of re-orientation is not supported by a single mechanism but involves two key subcomponents that are thought to be subserved by different cognitive systems (Julian et al, 2018; Julian et al, 2015). These are: the sudden recognition and recollection (context recognition) which requires the recovery and re-orientation to a new and relevant frame of reference; and, on the other hand, the retrieval of heading information in relation to the new frame of reference (heading determination) (ibid.). An individual is able to re-orient within an environment if certain spatial cues are available, which will facilitate context recognition and a re-orientation to a reference frame that supports an allocentric representation of the spatial layout. Then, heading direction needs to be aligned with an allocentric heading representation that will guide further movement towards the appropriate direction. Therefore, it involves the encoding of novel spatial information that is relevant to the task, the recollection of contextual information and the translation of information between reference frames

before heading determination. The objective here is to examine what sort of spatial properties serve as spatial cues that can trigger the self-location related processes (the context/place recognition mechanism).

### **1.2.2 Methodological approach**

The Aha! phenomenon is examined through an approach that brings together research fields related to the built environment (spatial analyses and environmental psychology) and research areas that focus on the brain's functions (spatial cognition and neuroscience). Thus, this thesis adopts a trans-disciplinary methodological approach and combines spatial analyses (isovist analysis and visibility graph analysis) with EEG recordings (electroencephalography). The spatial properties of the environment are considered to be important variables and investigated in conjunction with individual responses at the neural and behavioural level.

Elements or properties of the environment may act as spatial cues that contribute to self-localisation, which suggests that certain spatial conditions may be directly related to the experience of the spatial Aha! moment. Spatial learning and orientation depend on the environmental geometry and the “shape of the surrounding visible space” (Montello, 2007). The human brain appears to use several heuristics during the encoding and retrieval of spatial information in order to minimize the informational load. This can be done by anchoring, for example, the representation of objects to intrinsic frames of reference or by grouping them based on their spatial relations. This suggests that spatial variables such as local and global relations of spatial elements have a strong link with the way we perceive and remember spatial information. This view is supported by evidence from cognitive neuroscience that reveals a direct relation between spatial variables and neural firings. For example, according to recent findings (Marchette et al, 2015), the neural compass, that supports orientation mechanisms, is anchored to specific local spatial cues. Additionally, specific regions within the brain, such as the retrosplenial complex, the occipital place area, and the parahippocampal place area, have been observed as responding strongly to elements of the environment, such as urban scenes, buildings and rooms, landscapes and environmental boundaries (Julian et al, 2018).

Using quantitative environmental modelling we can formally describe the spatial properties of a certain location. For instance, space syntax methods (e.g. isovist properties) provide a quantitative technique that can be used to formally describe different locations in terms of their visuospatial local and global properties. Isovist can be used to describe the shape and complexity of spaces (Psarra and Grajewski, 2001) and research suggests that isovist measures and visibility graph analysis capture properties of space relevant to the experience (Franz & Wiener, 2005). Thus, this paradigm incorporates the context-based analysis to investigate the mental event of the Aha! experience of re-orientation.

The objective is to investigate the effect of spatial configuration on the human experience, how it engenders the emergence of experiential events, and how these events are manifested as brain dynamics. Recent developments in sensor technology and wireless communication provide a means to test scientifically derived ‘neuro-architectural’ hypothesis in virtual reality environments. Electroencephalography (EEG) is widely used in neurophysiological research but it has not been used much within the field of the built environment. The Emotiv headset, used in this thesis, is a wireless electroencephalography device (EEG) with 14 electrodes. It includes a software tool (Emotiv Testbench) that allows researchers to access and record the raw EEG signal and export the data for further processing. It offers, therefore, a reliable and appropriate method for brain data acquisition. This thesis introduces the use of this method of recording electrical brain activity from the human scalp (EEG) during navigation in virtual reality environments, which permits the investigation of individuals’ responses in relation to the spatial properties of the built environment.

### **1.2.3 The experimental paradigm**

The aim of the experimental paradigm used in this thesis is to recreate or simulate the experience of re-orientation after disorientation. An ecologically valid approach is therefore necessary in order to provide the range of possibilities that will allow the Aha! experience to emerge. For example, participants need to be in that state of mind that would permit or trigger the restructuring of their representation. Restructuring of the mental representation is usually preceded by mental impasses. Therefore, in this paradigm participants start in a state of disorientation. Spatial updating is disrupted because they appear suddenly in different random locations as if they were teleported



(e.g. simulating the 'exiting the tube station' experience). This increases the possibility of a sudden transition to a state of being situated and orientated with respect to the environment rather than a gradual transition that usually occurs during continuous spatial updating. They start exploring the virtual environment from these random locations and the underlying idea is that a sudden perceptual restructuring of the spatial information, at certain locations, will lead to a deeper understanding of one's position and the Aha! effect of changing the course of action.

The main focus of the analysis is on the mechanism of self-localisation after disorientation, and thus the Aha! effect of recognizing where one is, rather than the sub-process that follows, which is the moment of heading determination where one becomes aware of her actual heading. The objective is to isolate the effect of interest and examine where it is more likely for these Aha! moments to occur. The design of the virtual reality experiment and the data analyses (Chapters 3 and 4) are an attempt to assess the spatial properties that engender the moment of re-orientation by combining formal descriptions of the spatial context with the analysis of behavioural and neurophysiological data.

This enquiry, therefore, requires an approach that combines: (a) a reflective analysis of the human experience (experiential events) (b) a translation of the knowledge offered from lab-based experiments in the field of cognitive sciences into real-world complex and dynamic experimental conditions (mental events); and (c) a context-based quantitative analysis (spatial events). The experimental paradigm used in this research project enables gathering data (electrophysiological, behavioural and spatial) in relation to the spatial Aha! experience at the level of the individual.

## **1.3 The Events of Interest**

### **1.3.1 Experiential events: The phenomenon of spatial re-orientation**

In 1999, in the article entitled 'Strange horizons: Buildings, Biograms, and the Body Topologic', Brian Massumi argues against the idea that topology (of digital space) "contradicts the spatial reality of bodies and buildings", and expands his thoughts on the relation of the embodied experience and the notion of topology (Massumi, 1999).

His first argument is based on the experiential event of spatial re-orientation and starts with a reflection of his own experience of re-orientation after disorientation:

It appears I had been operating on two separate systems of reference: a predominantly proprioceptive system of self-reference operating in the tunnel-like bowels of the building, and a predominantly visual system of reference for the vistas outside. The two systems were not calibrated to each other. Or they hadn't been, until my **moment of hallucinatory truth** before the window [re-orientation]. Their respective spaces of orientation had been noncommunicating, like qualitatively different monads of experience (Massumi, 1999, p.179, emphasis added).

In his reflection on re-orientation, he refers to his re-orienting experience as involving some kind of coupling of two different systems or frames of reference. He describes proprioception as a self-referential sense that registers the displacements of the body or body parts and results in 'patches' of self-movement:

The resulting patch is a self-varying monad of motion; a dynamic form figuring only vectors...It is a qualitative space of variation referenced only to its own movement, running on autopilot. It is not a space of measure. To get a static, measurable, accurately positioned, visual form, you have to stop the movement. (ibid. p.183).

On the other hand, vision, as Massumi claims, is an “exoreferential single-sense functioning” associated with form in configuration. Cognitive maps are ‘visible forms grouped into fixed configurations’, and along with vision both function as memory devices (Massumi, 1999). Another significant non-geometric element that contributes and affects our orientation are landmarks, which according to Massumi “are what you habitually head for or away from. They trigger headings. Vectors. Landmarks are like magnetic poles that vectorize the space of orientation” (Massumi, 1999, p.180). He also refers to experiments on orientation with rats and human infants which support the idea that humans orient more by the 'shape of space', and claims that 'the emptier the space' the greater our ability to orient (ibid.). Our ability

to stay oriented in the built environment seems to be affected by the amount and distribution of visual information, the environmental shape and perhaps the presence or absence and configuration of landmarks.

The disturbing sense of disorientation is, therefore, an alarming signal of the 'disjunction between the visual and the proprioceptive'. The moment of re-orientation is a kind of 'new' dimension of experience where “vision’s conscious forms-in configuration feed back into the vectorial tendency-plus-habit of proprioception, and where proprioception feeds forward into vision” (ibid., p.182). It is an experiential event that involves an emergence of a 'hinge' relation between the two qualitatively different experiences of the senses or as expressed by Massumi: “Cross-sense referencing forms a third hinge-dimension of experience” (ibid. p.182).<sup>2</sup> And isn't it a qualitatively similar hinge-dimension of experience that is triggered when cross-referencing occurs with the punchline of a joke or when a solution pops up suddenly into our minds when we are trying to solve a seemingly unsolvable problem?

Koestler (1964) discusses this idea of cross-referencing under the concept of the 'bisociation of matrices'. The mental event of a sudden bisociation of two usually unrelated matrices is a common element in art, scientific discovery and in 'seeing the joke'. The 'bisociative shock' that accompanies this hinge-dimension of experience:

...has often the effect of making such implicit rules explicit, of suddenly focusing awareness on aspects of experience which had been un verbalized, unconsciously implied, taken for granted; so that a familiar and unnoticed aspect of a phenomenon – like the rise of the water-level – is suddenly perceived at an unfamiliar and significant angle (Koestler, 1964, p.108).

The link between creative thinking and the ability to perceive sensory input from a new, unfamiliar but significant angle is also present in Shon's (1967) approach where he discusses metaphor, analogy and the displacement of concepts. Displacement of

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<sup>2</sup> Massumi also refers to the elusive notion of place and comments that “place arises from a dynamic of interference and accord between sense dimensions” and “where we go to find ourselves when we are lost is where the senses fold into and out of each” (Massumi, 1999).

concepts refers to the situations where an old concept is shifted into a new situation in a way that makes the old concept change and extend (Schön, 1967). To illustrate this, he refers to the example of using metaphors when forming notions of simple geometric figures. He comments that a student can gain 'insights' into how to find the area of a parallelogram if she sees the rectangle in the parallelogram or the parallelogram as a 'distorted rectangle' (ibid., p.82).

Interestingly, a quite similar example is discussed in an article that attempts to explain – within the context of the gestalt theory – how we move from the form of grouping, to the form of shape and to the form of meaning (Pinna, 2010). According to these new gestalt principles, the perceptual sentence 'a distorted rectangle' or 'a rectangle distorted by something'<sup>3</sup> combines two important perceptual levels for the emergence of meaning: the 'ideal' and the 'contingent'. The 'ideal' (rectangle) is perceived amodally (amodal completeness) and the 'contingent', the irregular shape, is seen modally (modal incompleteness). In addition, the visual 'verb' (i.e. distorted) is considered by Pinna as the *happening* that gives rise to the perceptual meaning (Pinna, 2010). The *happening* appears to combine two qualitatively different experiences, the modal incompleteness and amodal completeness, and thus 'seeing-as' seems to allow for that new third 'hinge-dimension' to emerge.

Massumi's description of this hinge-dimension of experience is valuable in a sense that it is a personal report on how this moment of re-orientation is experienced subjectively. Similarly, a phenomenological account of the Aha! moment can contribute to our understanding of this significant experience alongside the relevant psychological, cognitive and neuroscientific studies. A relevant article that focuses on this first-person perspective on creative insights, offers some interesting ideas regarding the temporality of this simultaneous experience of something “surprisingly novel but profoundly familiar” (Cosmelli & Preiss, 2014). The positive affective feeling that accompanies this moment is usually expressed as a feeling of something “coming together”, “making sense”, “falling into place” or a “gap-filling” feeling. The latter is considered, by the authors, as being similar to the moment that follows

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<sup>3</sup> The example discussed in Pinna's paper is as 'a square beveled by something' (Pinna, 2010, p.54)

the tip-of-the-tongue experience which involves binding together the phonological information to the semantic information that was activated but incomplete.

The experience of “gap-filling”, during insights suggests that it “makes experiential sense if both ends of the gap are available at some point of the process” (ibid.). The “gap-filling” aspect of insight is past-oriented, according to the authors, and has a sharp reference to what was going on a moment before. The moment of insights “retrospectively illuminates the previously opaque context, and makes sense by referring to something that was, until a moment ago, unavailable” (ibid.). On the other hand, the future-oriented aspect refers to the representational change of the problem (i.e. perceptual restructuring) which opens up a new set of problems or as the authors comment “this generative, forward-looking aspect of the experience emphasizes the direction (or rather potential directions) toward which one is left facing, so to speak, as a consequence of one’s insight into the problem’s nature “(ibid.).

This “past-closing/future opening” structure is not only present in insightful thinking, but it is also associated with the idea of an embodied mind which supports perception-action by continuously minimizing prediction errors (ibid.). Within the field of spatial cognition, this link between past and future becomes even more relevant, since navigation is often based on such cognitive mechanisms. Interestingly, titles such as ‘Remembering the past and imagining the future’ in the field of spatial memory and imagery (Byrne et al, 2007) suggest that a similar two-sided structure can be observed during navigation. A current position within an environment is “embedded in the representation of the past and the expected future in terms of both location and time” (Buzsáki, 2006). The literature here illustrates several common aspects of the Aha! moment (e.g. gap-filling, hinge dimension of experience) and the experience of re-orientation and self-location. The moment of re-orientation, then, can be easily seen as an instance of the general concept of the Aha! moment, as another manifestation of this form of lived experience, the hinge-dimension of experience.

### 1.3.2 Mental events: Recording neural firings in real-world settings

Both notions of ‘spatial experience’ and ‘spatial cognition’ directly refer to the embodied condition of the human mind, which has evolved in order to function in response to its current habitual environment. Experiments that employ simple laboratory conditions, as opposed to ecologically valid approaches, may not necessarily generate representative neural responses that underlie the experience of real complex situations. Ecologically valid experimental designs allow participants to move, act and explore the environment in a natural way. Adopting an ecological approach is rather essential if we want to study cognition from the enactive<sup>4</sup> point of view, which suggests that “mind and world arise together in enaction” (Varela et al., 1993).

For instance, Spiers and Maguire (2006) adopted an inventive approach to the design of a virtual reality experiment, where they investigated the neural dynamics associated with the experience of driving a taxi cab in London. The process of navigation was unfolded into distinct events based on the content of participants' thoughts. The first-person perspective was assessed through retrospective verbal reports and was used to distinguish mental events. These content-based categorizations of mental events were then used to segregate the linked neural activity. This paradigm is a rather good example of a balanced and disciplined consideration of both third and first-person perspectives, which, according to Varela, may contribute to moving “one step closer to bridging the biological mind–experiential mind gap” (Varela, 1996).

In another real-world goal-directed navigation task, researchers used task events of new goals or detours to trigger the mental events of planning and re-planning the route to a certain location in order to investigate the neural representation of distance (Howard et al, 2014). Neural activity was studied in relation to movement events; during periods of movement on linear paths (travel periods) and pauses at street junctions (decision points). The design of this experiment not only addresses the need to 'read' neural activity in relation to the contextual information that guides

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<sup>4</sup> The notion of enaction emphasises the idea that cognition “is rather the enactment of a world and a mind on the basis of a history of the variety of actions that a being in the world performs” (Varela et al., 1993, p.9).

action but through the inventive use of impasses/detours and assignment of new goals, highlights also the problem-solving nature of goal-directed navigation.

The need for such inventive approaches when studying neural dynamics in real-world settings shows the difficulties in dealing with dynamic and complex conditions. Testing specific hypotheses on brain dynamics, and their relation to the properties of space, without reducing the richness of the spatial experience is not trivial because real-world situations cannot be easily controlled. In contrast, lab-based experiments are usually designed based on the presentation of simple stimuli, which allows researchers to test their hypotheses in a highly controlled manner. Even though these highly controlled experiments do not reflect the richness of the actual day-to-day human experience, their basic principles and findings can be translated into specific situations that align with real-world scenarios.

For instance, research on implicit and incidental sequence learning may offer insights into some of the basic principles that can be also found in the processes that are related to wayfinding. Wayfinding can be supported by route-based navigation which involves knowledge about sequences of events (episodes) and, in more familiar and large-scale environments, by map-based representations of the environment (survey knowledge), which are based on allocentric relations. Route knowledge of the built environment involves learning sequences of 'stimuli' that are encountered through movement. It involves the registration of sequences of point locations and related events. The sequences of events within the built environment have certain regularities since the environment was designed and built, in most cases, based on specific design principles. Researchers that study implicit learning of the regularities found in the structure of a sequence of events have reported the involvement of medial temporal lobe structures (a region responsible for memory formations and involved in navigation) when extracting regularities within a sequence (Rose et al, 2002). This permits the prediction of upcoming events and the development of adaptive behaviour and this type of learning can occur incidentally (*ibid.*). Research on incidental sequence learning (Frensch et al, 2003), suggests that insights into an implicit regularity and thus a switch from implicit to explicit knowledge occurs when one experiences a deviation from what is expected or predicted. This unexpected event leads to a surprise and the ability to verbally report an environmental

regularity. Interestingly, according to Neil Burgess (2008), it is highly likely that spatial learning (boundary-based learning) does not follow the rules of the dominant model of associative learning but depends on incidental learning.

Deviant events have also inspired Donchin's context-updating theory. The change in the representation, according to Donchin, is associated with the affective experience of surprise and may be triggered by novel and unexpected events. He argues that “events are remembered if they require, upon their occurrence, a restructuring of our mental models which is presumably what happens when we are surprised” (Donchin, 1981). The brain has a strong response to these deviant and unexpected stimuli and the relevant processes are manifested by an event-related component observed in the waveform of EEG recordings, which is called the P300 or P3 (ibid.). The P3 signals the occurrence of a deviation from what is expected and its relation to the hippocampal system is conceivable since the hippocampus seems to be sensitive to the contextual uncertainty of the environment (Harrison, Duggins, & Friston, 2006). Donchin, thus, suggests that the update or change of the mental representation is related to the experience of 'surprise' and to unexpected events. It is reasonable to assume that, during wayfinding, the sudden availability of novel information might lead to the experience of surprise and in an update or “a restructuring of our mental models”, if the information is relevant to the current task (e.g. finding a path to a goal). It might involve a perceptual restructuring of the task-related representation and a re-orientation to a different reference frame, a translation of information from one reference frame to another.

During navigation in an unfamiliar environment, people update their location in relation to their point of origin of movement, i.e. their starting location. That is, their navigation is initially based on path integration, that is keeping track of one's position in relation to the starting point, and 'constructing' a homing vector for orientation. Their exploratory behaviour is guided by the search for spatial cues. Novel environmental conditions can cause a reallocation of their attention and trigger processes that are related to the evaluation of these conditions in order to decide whether they can serve as 'target' cues for re-orientation. The recognition of such spatial cues may facilitate the transformation of the spatial information into an allocentric frame of reference. Therefore, from the spatial learning perspective,



moving from implicit sequence learning to explicit knowledge of spatial relations could be seen as moving from the autopilot of path integration to a more enduring allocentric representation of spatial knowledge.

### 1.3.3 Context events: Sudden change of visuospatial information

Mental representations of spatial relations have a rather complex and dynamic ‘nature’. They are greatly influenced by several perceptual and cognitive principles. Mental spatial representations are not exact map-like copies of the external environment, as the word ‘cognitive maps’ implies (Tversky, 1993), but rather “integrated and highly organized knowledge structures processed according to cognitive principles” (Klippel et al, 2005). Information of spatial relations is organized hierarchically into superordinate structures and subordinate clusters (Hommel & Knuf, 2000). Spatial chunking or clustering seems to occur where there are salient discontinuities or *discrete changes* (Klippel et al, 2012). For Barbara Tversky, the way the mind transforms and organizes knowledge is similar to that of solving problems; we parcel information into functionally significant components and group it into bigger categories that include other similar exemplars. Grouping and parcelling information where there are discrete changes is useful because it ‘allows inferences or predictions’ to emerge.

The notions of change and similarity, in terms of the information of the spatial configuration, are central in Penn's argument that 'cognitive space' is “topological or pre-topological in nature” (Penn, 2003). Presenting evidence from research on behavioural patterns of movement (using space syntax analysis), he attempts to describe a 'spatially plausible' theory of cognition. He suggests that “spatial learning may be more a matter of internalising the principles linking one dimension [local], which can be directly apprehended, to another which cannot [global]” and that the embodied mind has an inherent capacity in detecting correlations of this nature (ibid.). The 'cognitive space' is defined by Penn as “the space required to support the representation of this more global understanding of configuration based on some form of learning from experience” and suggests that this space might not be a metric space (ibid.). Penn's thinking finds support in Lin Chen's theory of early topological

perception<sup>5</sup>. According to Chen's theory, the extraction of global topological properties (invariants, such as connectivity and holes) is a basic factor in perceptual organization and claims that perceptual organization should be approached through the "perspective of transformation and perception of invariance over transformation" (Chen, 2005).

Penn's definition of 'cognitive space' is based on evidence from space syntax analyses, which is an environmental modelling tool that represents and quantifies aspects of the built environment. For example, relevant studies show that certain changes within the environmental context, such as the "average number of changes of direction encountered on routes", have an effect on the observed patterns of movement. In his attempt to find an explanatory theory for these observations he turns towards evidence from recordings of neural firings. He proposes that, based on these findings, it is possible that individuals integrate contextual information from movement in two stages: discrete locations encountered through movement are aggregated based on their "informational similarity" which implies a relative stability while the identification of relations between these aggregates probably occurs at point locations where "substantially new information is revealed", for example, at street junctions. Therefore, Penn claims that "detail is retained where it is vital for a decision, that is where information changes rapidly as a consequence of movement" (Penn, 2003). He proposes that the visibility graph (Turner et al, 2001) offers the means to 'imagine' this process of integration. In addition, Conroy's thesis provides evidence that at certain point location (configurationally integrated) that offer a *large amount of new visual information* (e.g. large isovist area) individual behaviour changes: humans pause and turn their heads to capture the new information. These locations are vital decision points for orientation since we turn our heads in order to decide the next direction of movement (Conroy, 2001).

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<sup>5</sup> The topological approach to perceptual organization provides a new analysis of the part-whole relationships: "holistic (or global) registration is prior to local analysis which goes beyond the notion that 'the whole is different than the sum of its parts'. A primitive and general function of the visual system is the perception of topological properties. The time dependence of perceiving form properties is systematically related to their structural stability under change, in a manner similar to Klein's hierarchy of geometries; in particular, topological perception (based on physical connectivity) is prior to the perception of other geometrical properties. The invariants at different geometrical levels are the primitives of visual form perception. These include, in a descending order of stability (from global to local), topological, projective, affine, and Euclidean geometrical invariants" (Chen 2005).

Consequently, while exploring a relatively unfamiliar environment (e.g. when the only knowledge of the environment was the one acquired by studying a map representation), the sudden availability of new visual information might trigger processes that are related to the update of the mental representation. The orienting response of the brain to changes in the environment will initiate processes of attention regulation to evaluate the significance of the stimulus, of the new visual information. As in the case of the oddball paradigm, if the stimulus is significant not only because of novelty, then memory operations will take place and the representation will be updated with the new information. If the new information involves a sense of familiarity, this might lead to processes related to access and retrieval of relevant information from the knowledge system of memory. The specific change in visuospatial information, can be recognised through memory processes as familiar without any further details or it can trigger recollection of relevant contextual information from the previous moment it was encountered (e.g. map of the built environment). The recognition of the specific location, as a significant spatial cue, can then result in the translation of the visuospatial information into an allocentric frame of reference, aligned with the knowledge acquired from the map of the built environment.

## 1.4 Hypotheses

Change is the fundamental force of experience, according to Massumi, and he suggests that 'affect' can be seen as 'a change in capacity' and the 'crossing of a threshold' (Massumi, 2006). In his recent book 'Politics of Affect' (Massumi, 2015) he comments that:

the experience of a change, an affecting being affected, is redoubled by an experience of the experience. This gives the body's movements a kind of depth that stays with it across all its transitions – accumulating in memory, in habit, in reflex, in desire, in tendency (Massumi, 2015, p.4).

In other words, 'a change in capacity' and the 'crossing of a threshold' in the environment are events that are inscribed in the mental representations stored in memory. Movement is guided through space by these changes.

The experience of change within an environment is the departing point for the thesis's hypotheses. Entering a location where there is a sudden change in the available visual information, a forced change in the direction of movement or a change in the available choices for movement, are several examples by which one can experience a 'crossing of a threshold' and/or a 'change in capacity'. More specifically, an affective experience (e.g. surprise) may emerge when passing by a small street to a large square or when an environmental shape with directional cues becomes available, or when there is a change in the grid or configuration.

The contribution of the environmental shape in orientation, but most importantly in re-orientation, is supported by evidence from several studies on spatial cognition (Julian et al, 2018). Different areas of the brain respond to the environmental context in different ways, such as recognising a certain location or place, anchoring mental representations to elements of the environment or processing relations between boundaries within a scene (ibid.). It is then reasonable to ask: 'Where, and in what sort of 'spatial situations', is it more likely that someone will realize their location and orientation, and experience the Aha! moment?

Environmental psychology studies this relationship between mind, body and space and provides the ground upon which the hypotheses of this thesis are formed. Environmental preference theories, within this field, attempt to combine psychological and spatial factors to explain elements of the human spatial experience and understand the factors that drive our exploratory behaviour (such as reward or affective mechanisms or even just the desire to learn). The affective response to certain environmental situations, which is expressed as preference, is an automatic and rapid evaluation of a certain location in terms of 'prospect' and 'refuge' or, according to evolutionary-based approaches within this field, in terms of promising new information with further 'exploration' and its comprehension, an 'understanding' of where one is in space. The second set of factors permit the updating and expanding of the 'cognitive map' (Kaplan, 1987). The two most known theories of environmental preference, Appleton's (Appleton, 1988) prospect-refuge theory and Kaplan's (Kaplan, 1987) 'information theory framework', appear to point towards different spatial properties and qualities of the environment as being stronger predictors of environmental preference.

The first relates to the notion of ‘spaciousness’. This is an important spatial quality and, according to theories in environmental psychology, spacious scenes are usually preferred because they are related to the notion of ‘prospect’. A sudden change in ‘spaciousness’, that is a sudden change in the amount of visual information is an environmental novelty that is closely related to the element of surprise. On the other hand, another important preference predictor is the factor of ‘complexity’ which is related also to ‘mystery’. Although ‘mystery’ is often associated with the experience of surprise, it is rather qualitatively different because it also includes the element of ‘predictability’ (Kaplan, 1987). Thus, this second relevant factor of ‘complexity’ is related to exploratory behaviour and the acquisition of new spatial information. It can be considered an informationally-relevant novelty, as opposed to mere novelty in terms of spaciousness. This distinction suggests that there are two ways of looking at the change of visual information; that is, a *change in the amount of visual information* or a *change in the complexity*. Therefore, the thesis will test the following hypotheses (these are explained in more detail in section 2.3.3):

$H_{\text{null}}$ : The Aha! experience occurs at random locations.

$H_{\text{spaciousness}}$ : The Aha! experience is more likely to occur at locations where there is a sudden change in the amount of visual information.

$H_{\text{complexity}}$ : The Aha! experience is more likely to occur at locations where there is a sudden change in the complexity of the visual information.

### **Related Brain dynamics**

The hypotheses of this thesis are examined based on the data collected from participants’ exploratory behaviour and on the data collected from the EEG recording (time-frequency analyses). These last paragraphs of the introduction offer a brief description of the brain dynamics that might be related to the processes that underlie the Aha! moment.

Encoding of unexpected and deviant spatial events involves the allocation of attention which might trigger memory processes. Such processes are usually

manifested by the P3 component, found in the time-domain analysis of the EEG signal (for more details see section 2.1.3). Several studies have used paradigms associated with the P300/P3 component to reveal the related time-frequency components and reported relevant modulations in the delta (0.5-4Hz), theta (4-7 Hz) and alpha (8-12Hz) frequency bands. Time-frequency analysis of the P3 component reported a novelty-detection related (P3a subcomponent) increase in frontal theta (4-8Hz) activity (Demiralp et al, 2001; Mazaheri & Picton, 2005). The frontocentral theta increase has been reported to scale relative to attentional load (Bachman & Bernat, 2018). Also, a frontocentral delta component was associated with stimulus evaluation (Yordanova et al, 2000) in an auditory oddball paradigm while a more recent study suggests that delta increase is related to sustained and complex stimulus processing (Bachman & Bernat, 2018). Widespread alpha decrease has also been reported for target stimuli (P3b subcomponent) (Kolev et al, 1997) and has been associated with perceptual processing, context-updating and maintenance of working memory (Mazaheri & Picton, 2005). Additionally, higher alpha power decrease has been observed for targets vs. non-targets for oddball experiments that involved different modalities (Peng et al, 2012).

Research on spatial memory has often reported an increase in theta activity during navigation associated with memory operations such as encoding and retrieval (Bischof & Boulanger, 2003; Mitchell et al, 2008). Increase in frontocentral theta has been reported during encoding of visuospatial information in working memory and during free exploration when compared with retrieval and baseline conditions (Jaiswal et al, 2010). Theta increases that have been reported during movement (or initiation of movement) compared with stationary periods may occur at a lower frequency range during virtual navigation peaking around 3.3Hz (Bohbot et al, 2017; Jacobs, 2014). Increased theta activity over the frontal areas has been observed during memory retrieval of “previously traversed segments” (Plank et al. 2010), “during critical phases of the navigation task”, generated in or near ACC reflecting spatial working memory demands (Lin et al, 2015), as well as over the frontocentral regions when a new shortcut to the goal becomes suddenly available (Javadi et al, 2018). The implication of the Anterior Cingulate Cortex, which is near central electrodes, has often been reported in decision-making and conflict resolution in insightful problem-solving. Central theta power has been reported to increase with

decision difficulty and was associated with increased reaction times (Jacobs et al, 2006). On the other hand, increased reaction times in another recognition memory study were observed of judgments “requiring the recollection of qualitative event information” during episodic retrieval, as opposed to judgments based on familiarity that can be made faster (Klimesch et al, 2001).

The main Aha! effect is the translation of spatial information between the two reference frames which is related to alpha power decrease. Alpha power decrease has been observed before backtracking behaviour during goal-directed navigation (Javadi et al, 2018) and has been related to the successful translation of spatial information between reference frames (Lin et al, 2015) and the process of retrieving information based on an allocentric reference frame (Chiu et al, 2012). Alpha decrease has been also associated with processing of sensory-semantic information (Klimesch et al, 2007). Klimesch (2012) suggest that alpha oscillations are related to semantic orientation, “the ability to be consciously oriented in time, space, and context”, and the controlled access to and retrieval of stored information. These cases have a strong connection to behaviour and cognitive processes, associated with the Aha! moment of re-orientation.

Consequently, the literature suggests that the Aha! experience is manifested in a decrease in alpha power at posterior areas and that a frontal and/or frontocentral increase in theta activity may contribute to this event since it has been reported during conflict resolution and decision-making. Alpha power decrease is expected to index larger memory 'update' and the mapping of egocentric viewpoints onto an allocentric reference frame, which is presumably what happens when we recognize where we are in relation to a large-scale environment. When participants encounter a task-related spatial cue, while exploring the environment, delta/theta activity is expected to show an increase reflecting gating mechanisms of attention during encoding of new relevant information. The new information related to these unexpected and deviant spatial cues will probably trigger memory operations that contribute to the re-orientation to a different frame of reference.

The EEG analysis is focused on the moment that participants encounter a spatial cue just before the response (stimulus-related) and the moment that they make a response

(response-related). The stimulus-related analysis examines the changes in the delta/theta power in relation to the moments when the visuospatial information suddenly changes. In the response-related analysis, trials are classified into test (alpha decrease/theta increase) and control (alpha decrease/theta increase) conditions in order to assess which spatial properties make a greater contribution to these brain dynamics. If spatial properties do not affect or contribute to the Aha! experience, then behavioural responses indicating re-orientation will occur at random locations and differences in brain dynamics will not be associated with differences in isovist values. But, if any of environmental psychology-related hypotheses is strongly linked to how we orient and navigate the built environment, then this will be reflected in the behavioural and EEG analysis, suggesting a strong relationship between the subjective individual experience and specific spatial properties.



## **CHAPTER 2      Literature Review**

## 2.1 The Aha! Moment in Insightful Problem Solving

Research on insights that employs neuroscientific methods has started growing at the beginning of the 21st century. Psychologists had focused on this subject much earlier using mainly classic paper and pencil insight problems, like the nine dots problem Duncker's problem, the six matchsticks, and the two strings problem, to name a few. Creative or insightful thinking seems to involve non-conscious implicit processing that results in a sudden awareness of the solution by the conscious mind. In contrast, the usual problem-solving process relies on analytic and explicit thinking. Tasks used in creativity research include problems that require a semantic restructuring such as riddles, brainteasers or remote compound associations or involve a visuospatial restructuring such as chunk decomposition, the nine dots problem, the number reduction task or matchstick problems.

The chapter reviews the influential works of Koestler (1964) on creative thinking and Boden (2003) on types of creativity and discusses their possible relation to navigation. Special attention is given as well at the emergence of perceptual meaning as discussed by Pinna (2010) and creativity in vision which arises as a response to visual complexity. It then focuses on the notion of insights and the main features of the insight process (section 2.1.2). Several studies have examined the cognitive neuroscience of insights. A discussion of the main findings can be found in four influential reviews (Dietrich & Kanso, 2010, Shen et al., 2013, Shen et al., 2018, Kounios & Beeman, 2014) which are summarised in section 2.1.3. Although research on insights has employed different methods to analyse the brain related dynamics (e.g. fMRI, PET, EEG), the number of studies using event-related potentials (ERPs) is larger than studies using time-frequency decomposition of the EEG signal. The event-related potential (ERP) studies on insight suggest that a P3-like component might be strongly related to the underlying processes of insight.

A key feature of the Aha! experience is the re-orientation of one's thinking that results in a reconstruction of one's representation. The reorienting ability of the human brain is crucial in terms of survival; it is an '*orienting reflex*', an immediate response and switch of attention to a novel, unexpected and relevant stimulus that is outside of the current focus, which might be threatening or advantageous (Corbetta et

al, 2008). Donchin argues that there are similar attributes between the '*orienting reflex*' and the P3 component as they are both a kind of mismatch detectors (Donchin, 1981). They reflect the brain's response when there is a mismatch between an internal representation of one's current environment and an unpredictable stimulus. This leads to the experience of surprise and, if the environmental stimulus or cue is related to the task at hand, the updating of the mental representation. Unexpected events and the experience of surprise could be also related to the transition from implicit learning to explicit reportable knowledge. Researchers suggest that insights should be investigated within this context using implicit learning paradigms (Haider & Rose, 2007). Additionally, these mechanisms may not only be related to one-shot incidental learning in insightful problem solving but to incidental spatial learning as well.

### **2.1.1 Creative Thinking and Problem Solving**

Several scholars have tried to demystify this exceptional ability of the human mind to combine old ideas into new, to discover new, surprising and valuable solutions to problems, to create art and to appreciate the humour. As we have seen in the introduction, Koestler (1964) in his attempt to understand the act of creation as expressed in humour, science and the arts, he develops a theory of human creativity based on the idea that creative thinking involves the 'bisociation' of previously unrelated matrices. These matrices are organised subsystems of knowledge that represent habitual associations of elements within specific frames of references. The Aha! experience emerges when elements are reorganised based on two different matrices that were previously unrelated. That is, the Aha! moment is associated with the recognition of 'bisociations'.

Margaret Boden adopts a perspective from the field of artificial intelligence and investigates the components and types of creative thinking (Boden, 2003). She defines creativity as the ability to come up with ideas or artefacts that are new, surprising and valuable. Novelty has two levels, it might be new to the person that came up with the idea (psychological creativity) and/or new to human history (historical creativity). The element of surprise, on the other hand, has three meanings which are related to the three different types of creativity as Boden suggests (ibid.). Combinational creativity is surprising because something unfamiliar or unlikely

emerges out of an unfamiliar combination of familiar ideas that makes sense. This requires a rich store of knowledge and the creation of new interrelations. Realising that a particular idea is part of a familiar style of thinking is surprising because it allows seeing new possibilities within a pre-existing conceptual space. This belongs to the type of exploratory creativity which is driven by a “What is around the corner?” sort of questions. The third type, transformational creativity, entails a change in the thinking style, a transformation of the conceptual space which allows for previously inconceivable thoughts to emerge (ibid.).

The transformation of the representation or the perceptual restructuring that takes place during creative problem solving is usually the result of impasses that are caused by a misleading initial representation. This view comes from early work of Gestalt psychologists (i.e. Köhler, 1925) and is still supported by several cognitive psychologist who argue that the initial unsuitable representation is overcome by restructuring the elements of the problem (Knoblich et al, 1999; Knoblich et al, 2001; Luo et al, 2006; Shen et al, 2013b). Two classic insightful problem-solving paradigms are shown in Figure 2.1-1 which are good examples that illustrate these processes. In the nine-dot problem (where one needs to connect all dots with just four lines) individuals may experience an impasse when they are not able to find the next line to draw that can pick up a sufficient number of dots (Knoblich et al, 2001) because the imagined square created by the spatial layout of the dots (based on the gestalt principles of grouping) limits the solution space of possible lines. The solution, therefore, requires a sort of visuospatial restructuring. The case of the matchstick problem involves a restructuring of spatial relations of the matchstick that form the values or the operators (i.e., plus, minus, and equal signs) and that results in the transformation of the meaning as well (the arithmetic values). In this paradigm, the individual needs to make the equation correct by moving just one matchstick. The roman values and operators form meaningful perceptual chunks which act as fixed elements in the initial representation. This leads to impasses which are evident by eye movement data analysis and result in longer fixation times (Knoblich et al, 2001). The change in the representation occurs when the fixed elements are decomposed, and the spatial relations of the matchstick are reorganised. This moment causes a shift in attention allocation and eye fixation to these perceptually stable elements (ibid.). In accordance with the gestalt theory, the researchers of this

eye-tracking study, indicate that thinking begins when “the ‘perceptual’ field is in a state of imbalance or tension. A solution appears in conscious once the perceptual field reorganizes itself into a better, more harmonious or balanced state” (Knoblich et al., 2001b); a view that converges with recent Gestalt theories on the emergence of meaning in visual perception (Pinna, 2010).

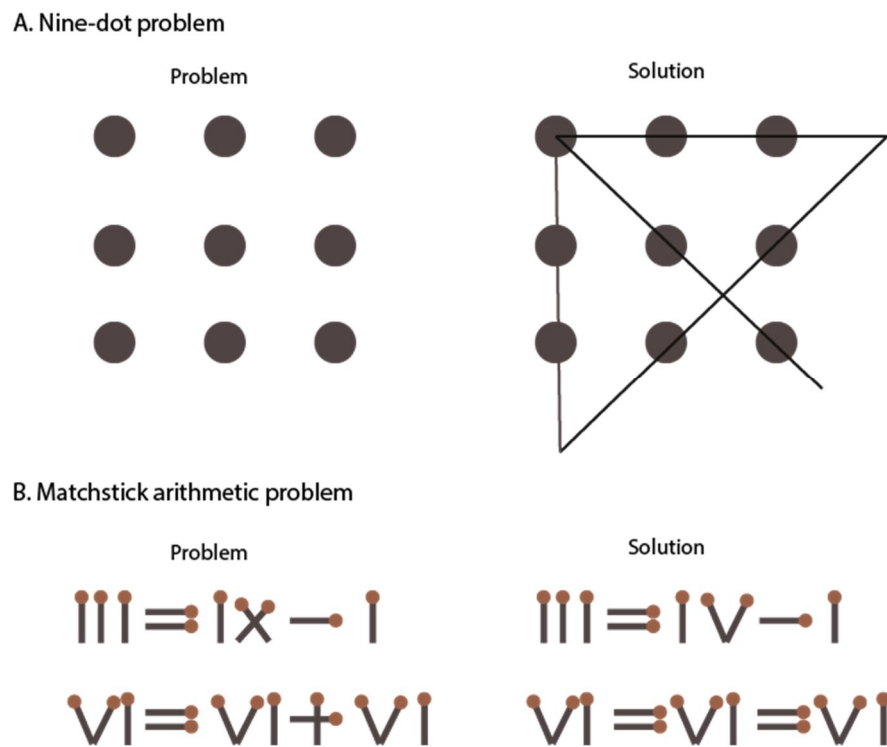


Figure 2.1-1. Classic insights problem. In the nine-dot problem, participants need to connect all dots with just four lines (A) and in the matchstick problem the individual needs to make the equation correct by moving just one matchstick (B).

The Gestalt laws explain the form of grouping but not how we pass from the form of grouping to the form of meaning, that ‘harmonious and balanced state’. The problem-solving examples mentioned earlier illustrate transformations of elements that are grouped because of their visuospatial (square grouping of dots) or semantic (roman numerals and operators). Grouping of mental objects (that include things, places, and events) seem to follow part-whole relations, according to Tversky (Tversky, 2005 ). The perceptual objects of everyday life seem to have at least three main forms of organisation: they are made up of elements that are grouped and segregated but appear as shapes and “signify one or more meanings related to other shapes and meanings” (Pinna, 2010). New gestalt theories of the perceptual

organisation focus exactly on this relationship and the emergence of meaning in visual perception (see also section 1.2.1).

A series of phenomenological experiments on several visual stimuli are analysed by Pinna (2010) with the objective to study the continuum from the 'form of grouping', and 'form of shape' towards the 'form of meaning'. She comments that perceptual meaning can be considered as some sort of “non-verbal primitive language”. The perceptual meaning emerges from “normal, spontaneously conveyed vision” and involves two perceptual levels: the 'modal partialness' (heterogeneity) and the 'amodal wholeness' (homogeneity).<sup>6</sup> In the perceptual sentence of this primitive language, the 'verb' -a 'happening'- expresses properties, existence or shows the action performed and the state attributed to the 'subject' e.g. a 'square bevelled by something'. According to Pinna, a special case within the larger frame of 'happenings' is Gibson's notion of 'affordances', defined as the possibilities of action in the environment. 'Happenings' emerge as meanings to create homogeneity and explain differences, variations and lack of homogeneity (ibid.). Small variations in the 'happenings' may cause instability in the perceptual system which is “the source of mutations and creativity of the meanings”. Pinna notes that “this is the basis of the creativity of vision” (Pinna, 2010).

An interesting conclusion from these new gestalt principles of perceptual organisation is the relation between the creation of meaning and the change in complexity. A change in complexity is of great interest because is directly related to one of the hypotheses that may explain the emergence of the spatial Aha! experience, as mentioned earlier in the introduction (for more details see section 2.3.3). According to Pinna, the increased complexity that appears when moving from the form of grouping, to shape and meaning results in the reduction of the information load (the number of contents or disparate components) by the increasing of

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<sup>6</sup> The main definitions related to the perceptual meaning are the following: “D1: We call 'perceptual meaning' what is expressed, indicated or conveyed by a grouping and a shape through the 'amodal wholeness' and the 'modal partialness' (see the next definitions). D2: We call 'amodal wholeness' the vivid percept of object unity and wholeness even though the observer does not actually see a contour in regions where the completion of the whole object occurs at a level after the 'happening'. D3: We call 'modal partialness' the clear modal emerging of a specific happening that occludes the completion of one part of the complementary region, such as a square, that appears as the whole.” (Pinna, 2010, p.69)

simplicity (ibid.). Pinna claims that even if there is a distinction between seeing and thinking, the perceptual language can be considered as providing “the foundations of more refined and elaborated cognitive meaning” since it is associated with higher-level cognitive processes that are related to past experience. These processes, involved in the emergence of the perceptual meaning, can be related to knowledge acquisition mechanism or as Pinna states to “the capacity to abstract from the experience of many particulars or to minimize the number of elements” and at the same time “the capacity to maximize the information and then to create new meanings in a highly creative process” (Pinna, 2010). This perhaps is also related to knowledge acquisition during navigation and the sudden transformation of the visuospatial information (e.g. complexity of environmental shape) into higher-order representations.

In Boden’s (2003) work, the links between creative thinking and navigation are more direct. She uses analogies of exploration of geographical space to explain exploratory creativity, and the idea of transformation of ‘maps inside our heads’ to describe the surprising effect of transformational creativity (ibid.). These analogies offer the possibility to examine these two types from the perspective of wayfinding and spatial problem-solving. Exploratory creativity can be seen as experiencing new spatial locations or situations that were not previously encountered through the habitual route to the goal. Although this may enrich the mental representation of spatial information (style of thinking), it does not actually transform it. On the other hand, transformational creativity, which, as described by Boden (Boden, 2003) involves the transformation of the conceptual map, suggests the reorganisation or restructuring of the spatial information into a representation that is not restricted by the temporal order of events as experienced by the individual. It rather involves the transformation of the spatial mental representation based on a new frame of reference e.g. an allocentric. This restructuring permits ‘inventing’ or imagining new routes between locations that were not previously experienced within the same temporal sequence. It is possible that this case is also an instance of Koestler’s concept of ‘*bissociation*’ of matrices.

Among the categories of matrices where 'bissociative' thinking may emerge, as Koestler (1964) suggests, '*chronological matrices*' seems to be the most relevant category to the representation of spatiotemporal information. He comments that:

Chronological matrices, naively regarded, seem to be linear chains of events, but are of course nothing of the sort. They are multi-dimensional structures in semantic space, governed by a diversity of selective codes, whose criteria of relevance are often quite indifferent to temporal order. (Koestler, 1964).

This description seems to refer to matrices that go beyond the representations of episodic (autobiographic) memories and expand towards conceptual dimensions and semantic structures.

Interestingly, there seem to be some common elements between Koestler's chronological matrices and theoretical perspectives within the field of spatial cognition (see section 2.2.3), which explore the relation of the hippocampus to context-based episodic memories and higher-order structures (e.g. context-free). For example, one viewpoint is that the hippocampus is not only related to memory, but it also plays a central role in the integration of information across experiences creating higher-order structures (Koster et al, 2018). Another view, based on the relational memory theory, proposes that the juxtaposition of several episodes of temporal sequences of events, supported by the hippocampus, gives rise to context-free semantic memories (Eichenbaum and Cohen, 2014). The relational theory suggests that the role of hippocampus might not be limited to spatial navigation processes (ibid.). In addition, early research on insightful problem solving that suggests that the "reorientation of one's thinking could be subserved by a similar hippocampal function to that of reorientation in navigation" (Luo & Niki, 2003). Reorientation in navigation, therefore, appears to entail a switch or a transformation of the representation to higher-order structures (e.g. allocentric representations), analogous to a 'bisociation' of chronological matrices.



### 2.1.2 Salient Features of Insights

To narrow down the field of enquiry I will focus on the notion of insight and how it can be defined in the context of problem-solving. A common non-scientific description of insight is any deep realization irrespectively of its suddenness (Kounios & Beeman, 2014). However, this is rather a very broad definition. In contrast, a very narrow definition would be: “a sudden solution to a problem preceded by an impasse and problem restructuring and followed by a positive emotional response” (ibid.). Insight describes the exceptional cognitive and emotional process in problem-solving that elicits the Aha! Moment. Insights are not restricted to any particular level of understanding and it may occur in different domains of cognition such as perception, language comprehension or problem-solving (ibid.).

The experience of insights, or the Aha! experience is a new understanding that emerges into conscious awareness with a sudden abruptness (Mai et al, 2004; Shen et al, 2013b). This view can be traced back to the early works of Gestalt psychologist and suggests that insight learning is not an incremental associative learning process but sudden one-shot learning that requires a transformative step (Luo et al, 2006). In this situation, the individual initially feels unable to find the correct answer when suddenly and unexpectedly the solution appears clearly into awareness with a positive emotional effect and a feeling of surprise. It involves a transformative switch and a shift from a state of not knowing to a state of knowing. The Aha! moment often emerges after a period of unconscious cognitive processing and therefore, the experience appears as disconnected from the stream of consciousness. In contrast, during deliberate analytical thinking, there is a conscious and incremental awareness of the solution (Kounios & Beeman, 2014). Therefore, insight can be defined as:

Any sudden comprehension, realization, or problem-solution that involves a reorganization of the elements of a person’s mental representation of a stimulus, situation, or event to yield a nonobvious or nondominant interpretation. Insight is sudden, but it is preceded by substantial unconscious processing (ibid.).

Alternatively, a definition that refers to the specific components involved in the process of insights during problem solving would be “the reorientation of one’s thinking, including breaking of the unwarranted ‘fixation’ and forming of novel, task-related associations among the old nodes of concepts or cognitive skills” (Luo & Niki, 2003).

To explore the cognitive mechanisms of insights and describe how impasses emerge, researches often refer to the Representation Change theory (Knoblich et al, 1999; Luo et al, 2006; Wu et al, 2009). According to this theory, a bias of prior experience results in grouping the elements of the problem in prefixed perceptual chunks (Figure 2.1-1). This habitual pattern of elements’ organization constrains the representation of the problem space and limits the space of possible solutions. When these initial representations are misleading or incomplete, people experience impasses and conflict (Shen et al, 2013b). In these cases, a perceptual restructuring of the problem representation is needed and relaxation of constraints of the problem space is required to extend the space of possible solutions. In other words, one needs to ‘break’ and shift the initial mental set to find the solution. Several researchers support this idea and their studies are focused in investigating insight problem-solving processes in terms of its four salient features; mental impasses or ‘fixation’, perceptual restructuring, deeper understanding of the problem and the solution path and finally the Aha! feeling of suddenness and correctness of the solution (Sandkuhler & Bhattacharya, 2008; Shen et al, 2013a).

Mental impasses are “a state of mind that is accompanied by a subjective feeling of not knowing what to do and a cessation of overt problem-solving behaviour” (Knoblich et al, 1999). The attentional load from the excessive focus on inappropriate cues leads to mental impasses and results in a discontinuity in the solver’s solution path. A shift of attention ‘outside’ of the problem space may result in the recombination of the problem’s elements. This allows the emergence of new meanings and novel associations from previously unperceived regularities. A shortcut to the solution may appear or even a change of the problem’s initial goal. At these moments there is a deeper understanding of the problem and of the limitations suggested by the initial representation; the space of possible solutions is expanded. Creativity researchers often refer to this stage as the ‘incubation stage’ where a

suspension of conscious mental effort to solve the problem permits the reorganization of information by “unconscious or partially conscious processes of the mind”, which finally leads to the unexpected flash of illumination (Dorfman et al, 1996).

Thus, insight is akin to a sudden transition from implicit knowledge to reportable knowledge. The transformative switch of the representation results in explicit knowledge. Haider and Rose (2007) propose that the insight process should be investigated within this context using implicit learning paradigms instead of insight problems. In support of this view, researchers on insights also highlight the importance of taking a process-oriented approach instead of a problem-oriented approach: “If one conceives of insight as a specific problem-solving process that accompanies solutions on certain laboratory puzzle problems, then this effectively limits the type of research that will be conducted and the implications that can be drawn from that research”(Ash et al, 2012). The transition from implicit learning to explicit knowledge describe the way we can acquire reportable knowledge.

The acquisition of knowledge, from the associationism’s point of view, is a result of a gradual process of associations of events that repeatedly co-occur (ibid.). This suggests a trial and error approach to the learning process. On the other hand, the Gestalt approach seeks to understand a qualitatively different process of learning, one that is based on the relations “that are formed based on meaningful conceptual and functional characteristics” (Ash et al 2012). Insightful learning, as opposed to associative learning, does not entail the acquisition of new knowledge in a gradual manner but involves processes that result in sudden one-shot learning.

Researchers studying implicit contextual learning with fMRI have reported the involvement of medial temporal lobe structures (responsible for memory formations and involved in navigation) in extracting regularities within a sequence (Rose et al, 2002) which allows the development of adaptive behaviour. The detection of regularities within a sequence enables the prediction of upcoming events and this type of learning can occur incidentally (ibid.). This type of learning is also found to be related to spatial cognition and spatial memory. Burgess (2008) discusses that is highly likely that spatial learning does not follow the error-correcting learning rules

(‘prediction error’) of the dominant model of associative learning but is rather “incidental, occurring independently of performance, motivation, or prediction error”. The hippocampus supports incidental learning of environmental boundaries and thus supports one-shot learning of events and their context as opposed to “semantic knowledge acquired slowly over multiple exposures”. Learning in relation to landmarks, on the other hand, is rather closer to associative learning theories (Burgess, 2008).

Research on incidental sequence learning usually focuses on the conditions under which humans acquire explicit reportable knowledge through implicit or non-conscious learning (Rünger & Frensch, 2008). According to the Unexpected Event Hypothesis (Frensch et al, 2003), insights into an implicit regularity, and thus a switch from implicit to explicit knowledge, occurs when one experiences a deviation from what is expected or predicted. The Number Reduction Task (NRT) is a good example for exploring the process of insight within the context of incidental implicit learning. In this task, participants are presented with a sequence of numbers and they are asked to compute the next number entry based on two given rules. However, there is the same hidden pattern of regularity in every task. As soon as participants gain insight to this regularity their reaction times drop. Researchers suggest that this change of behaviour - faster responses- is what triggers the explicit searching of the knowledge that has been acquired through implicit learning. According to Haider and Rose, among the advantages of using implicit learning paradigm to study insights is that the features of this task, in this case, numbers as stimuli, can be easily modified and that researchers may study the development of insights on a trial-by-trial basis (Haider and Rose 2007). In summary, the unexpected-event hypothesis suggests that the experience of a deviation from what is expected leads to a surprise, which can result in the ability to verbally report an environmental regularity.

### **2.1.3 The Insightful Brain**

During the last decade researches started studying the neural mechanism of insights using neuroimaging technology, such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG). Insight problem-solving paradigm used in traditional insight research (e.g. the nine-dot and matchstick problems) do not meet the requirements of neuroscientific

methods since these methods require multiple trials and precise timing (Luo & Knoblich, 2007). Hence, neuroscientific research had initially two main problems to face: choosing appropriate experimental paradigms that would involve many trials and that would not exceed the time-constraints of the data acquisition system. Reviews of neuroscientific research on insight have attempted to study the relevant findings based on the methodologies used, such as fMRI and EEG, (Dietrich & Kanso, 2010), in terms of the brain areas involved in the process of insight and their role (Luo & Knoblich, 2007), in terms of the content of the experimental task (Sawyer, 2011) or by focusing only on studies that fulfil certain methodological criteria (Kounios & Beeman, 2014). Creativity researches have focused on the resting-state brain activity that is associated with insight solutions (Kounios et al, 2006) while others have attempted to deconstruct insight and study the four main components of the process (Luo et al, 2006; Sandkühler & Bhattacharya, 2008). Although a lot of innovative experimental tasks are employed since 2000, research on insight is still in its initial state since it is non-trivial to identify these internally induced unpredictable moments of exceptional thinking.

Deitrich and Kanso (2010) review studies using electroencephalography (EEG), event-related potentials (ERP) and brain imaging (PET, fMRI), and report that the anterior cingulate cortex (ACC) plays a critical role in insights. It initiates processes that are related to the breaking of the fixed mental mindset. According to the review, activity in the prefrontal cortex often accompanies insights. However, different studies have reported the involvement of different prefrontal areas and it is likely that the prefrontal activity may only reflect task difficulty. The reviewers also report that insights are associated with activity in temporoparietal regions such as the superior temporal gyrus (but only for paradigms requiring verbal processing) and the hippocampus (*ibid.*).

Another review concludes that a distributed functional network of brain areas (Figure 2.1-2) forms the neural basis of the ‘insightful brain’ (Shen et al, 2013b). The cingulate cortex - particularly the anterior cingulate cortex (ACC) - acts as an ‘early warning’ system of potential impasses and is involved in detecting and monitoring cognitive conflict between old and new ideas or representations. Activity in the prefrontal cortex is related to the shifting of the mindset. The medial temporal lobe,

the hippocampus, parahippocampus -and superior temporal gyrus (STG) in cases involving language processing- are involved in the formation of novel and effective associations whereas the parieto-occipital region is implicated in the effective transformation of the problem's representation (ibid.).

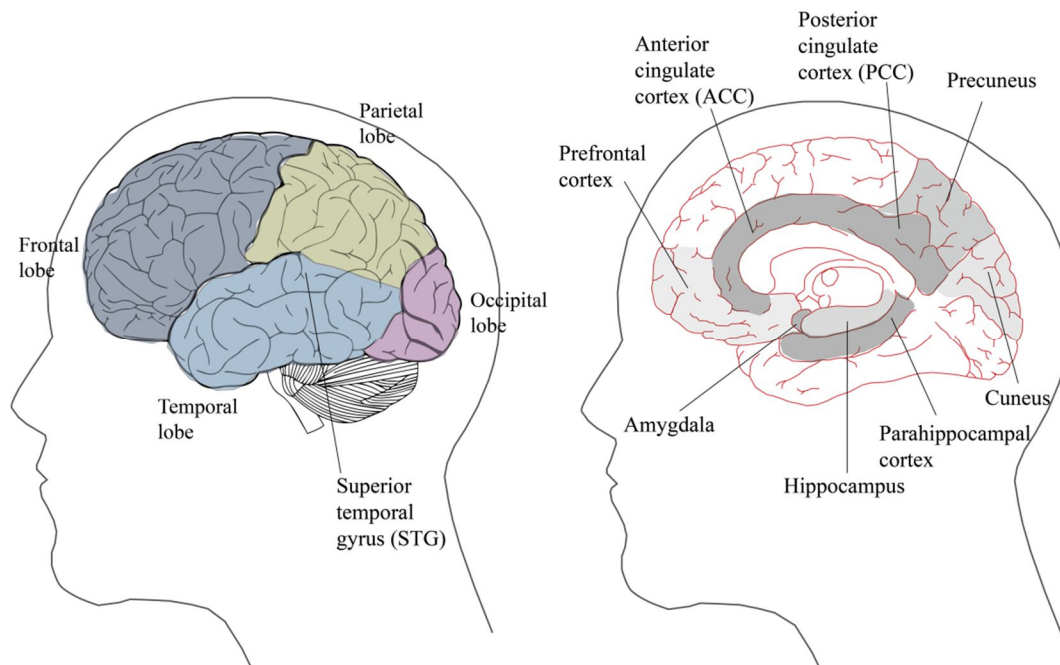


Figure 2.1-2. Brain's anatomy and main regions involved in insightful thinking. A visual summary of the relevant literature review.

A recent review on the neurodynamics of the insight process, reports that the prefrontal cortex is related to the incubation-like stage of insightful problem solving and is a working stage that precedes the breaking of the mental set (Shen et al, 2018). The anterior cingulate cortex (left hemisphere), as the review reports, is involved in the mental preparation and incubation stage of insights and the occipital regions (middle occipital gyrus) in “visualizing or re-encoding the problem space to mentally re-establish more appropriate representations of the given problem” (ibid.). The hippocampus (medial temporal lobe) is not only involved in spatial and relational memory but in forming remote and novel task-related semantic or episodic associations as well, which predicts its relation to the process of insights (ibid.). The hippocampal gyrus (right hemisphere), a brain area involved in the establishment of new, non-salient semantic associations is related to the general pattern of insights, as the review suggests. In addition, it contributes to the illumination-like stage where new associations trigger the emergence of the solution and the spontaneous insight

experience. The reviewers suggest that the amygdala is also related to this stage and the positive emotional response that accompanies the Aha! experience (Shen et al, 2018).

Research on creative problem solving provides evidence that favour the association of insight solutions with greater activity of the right hemisphere (Jung-Beeman et al, 2004; Kounios & Beeman, 2014; Kounios et al, 2008) while other reviews suggest that insights involve areas of both hemispheres (Dietrich & Kanso, 2010; Qiu et al, 2008; Shen et al, 2018). Kounios and Beeman (2014) in their review of a small number of studies that share similar methodologies argue that important components of insight are related to the right hemisphere (especially the right anterior temporal lobe). Support of this view comes from a study on brain stimulation, where researches applied direct stimulation to the right frontal-temporal cortex and simultaneous inhibition of the left frontal-temporal cortex and observed an increase in the solution rates of the classic nine-dot and matchstick insight problems (Chi & Snyder 2012 in Kounios and Beeman, 2014).

One of the first event-related fMRI studies on insights was performed by Luo and colleagues (Luo & Niki, 2003). The authors used Japanese riddles as a problem-solving task and the presentation of the correct answer to trigger the Aha! phenomenon. Results showed that the Aha! event activated, among other areas, the right hippocampus. The researchers suggested that breaking a mental fixation and forming new task-related associations activate the hippocampus through a 'reorientation-like process'. In a series of studies on insights, researches (Bowden & Jung-Beeman, 2007; Jung-Beeman et al, 2004; Kounios et al, 2006) used a compound remote association task (CRA). In this task, subjects must find a solution by creating new semantic remote associations between three provided words (pine, crab, sauce) and a fourth one (apple as a solution) that when added to each of them changes their meaning (pineapple, crab apple, applesauce). Insight solutions were classified as such according to subjective reports. The anterior superior temporal gyrus (aSTG) was more activated for insight solutions than non-insights (Jung-Beeman et al, 2004). Literature suggests that this area is important for distant lexical and semantic relations (Bowden & Jung-Beeman, 2007) and it has been only

reported in studies involving language processing but not in other paradigms, such as implicit learning or Guilford's match problems (Dietrich & Kanso, 2010).

In contrast, the anterior cingulate cortex (ACC) has been reported in studies using diverse insight problem-solving tasks for example in solving puzzles with different underlying principles of the structure as opposed to puzzles using the same structure (Luo et al, 2004b). It has also been reported when participants were presented with hints to generate alternative interpretations to critical concepts of sentences that appear incomprehensible (Luo et al, 2004a) as well in several event-related potential studies that will be discussed towards the end of this section. Activity in the ACC was also greater, just before the presentation of the problem, for people who solved the CRA with insights compared with cases that were not reported as insightful (Kounios et al, 2006). The activity in the ACC during the preparation stages was associated with changes in midfrontal alpha power, although the researchers noted that prior studies have found ACC activity to be reflected by changes in theta power (*ibid*). The alpha power (9-10 Hz) during preparation was less for insights cases compared with cases where no responses were provided before the end of the trial. Insight preparation showed less alpha activity over midfrontal, left and right temporal and right inferior frontal compared with preparation stage of non-insight solutions (Kounios et al, 2006).

An earlier study using again the CRA task reported a burst of gamma activity (40Hz), associated with insight solutions, that was observed 300 milliseconds before participants button-press response (Jung-Beeman et al., 2004). The increase in gamma activity was observed at the electrodes over the right anterior temporal lobe and might be associated with the increased activity at the right STG which was also observed for insight solutions (*ibid.*). However, the gamma response was present during the post-solution period which suggests that it might be related to affective processes of the Aha! experience (Sheth et al, 2009). The researchers also reported a burst of alpha activity (10 Hz) for insight solutions over right occipital cortex which was apparent from approximately 1.4 to 0.4 s before response (Jung-Beeman et al., 2004). In another study using the same task, upper alpha power (10-12 Hz) increase was observed for trial where a presentation of a hint led to a correct solution (Sandkühler & Bhattacharya, 2008). On the other hand, alpha power decrease in



right prefrontal areas was reported as the neural correlate of conscious restructuring (ibid.). An earlier study comparing cases of difficult word sequences that require insights with easy sequences<sup>7</sup> reported alpha power decreases at parietal cortex and delta and theta power increase in right anterior-temporal areas, for the insight task (Danko et al, 2003).

Changes in beta and gamma power have been also observed for insight solutions. Transformative reasoning in insight problems (verbal puzzles) was associated with decreased beta power (13-30Hz) at parietal and parieto-occipital areas (Sheth et al, 2009). Increased gamma power over right frontal, frontocentral and centroparietal areas was observed -over the right parieto-occipital region- for correct solutions as well as for trials where participants reported an Aha! experience vs. non-Aha (ibid.). Increase gamma activity was also observed in a study using the CRA task for correct vs. incorrect solutions (Sandkühler & Bhattacharya, 2008). An increased theta activity over parieto-occipital regions was also observed before the moment of mental impasses (ibid.)

Two issues that should be mentioned here is that non-verbal problem solving (as opposed to the CRA) may be related to different brain areas. Also, the distinction of insight and non-insight solutions in the CRA task does not directly control for the occurrence of a representational change as in studies that compare different cases of similar problems that may or may not require chunk decomposition. Additionally, the CRA problem could be a case of combinational rather than a type of transformational creativity that involves a switch in the representation. Sheth and colleagues (2009) also noted that remote association tasks require verbal fluency and rather than involving a link between disparate knowledge domains, it is restricted to the lexical domain. These issues, along with the variability in the tasks and methods, may contribute to the conflicting views regarding the relation of insightful problem solving and alpha activity. While Fink and Benedek (2014) argue that increase in alpha activity over frontal and parietal areas is associated with insightful solutions,

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<sup>7</sup> For the difficult sequence task participants had to find a link between a sequence of 12 semantically different words using associated words (nouns) and for the easy task they had to give five concrete examples that belong to a given word category.

Deitrich and Kanso (2010) highlight that a consistent finding in EEG studies on insights is the decrease in alpha power over frontal, temporal and parietal regions.

#### Event-related potential (ERP) studies and the P3 component

Researchers have also focused on the electrophysiological correlates of insights using the event-related potential method (ERP). Different experimental tasks have been used to study insightful problem solving such as riddles, Chinese logogriphs<sup>8</sup> or generation of new Chinese characters by adding a stroke (Mai et al, 2004; Qiu et al, 2006; Qiu et al, 2007). In these experiments, researchers classified as an Aha! condition the unexpected comprehension of a provided answer or hint, after failed attempts of the subject to solve the problem. Mai et al (2004) found that the ‘Aha! answers’ elicited a more negative deflection than ‘No-aha answers’ at the frontocentral region between 250ms – 500ms (Peak latency at N380), after the presentation of a keyword to the difficult riddle, as well as a parietal late positive component (LPC) between 500ms - 800ms. The dipole analysis<sup>9</sup> localized the generator of the N380 at the Anterior Cingulate Cortex (ACC). The authors proposed that the N380 reflected the Aha! effect of breaking the mental set. For Qiu and colleagues (2006) the Aha! condition was when participants could understand the given answer and it was not what they initially guessed. They reported a similar negative deflection at the time window of 250ms - 400ms (N320) at the right temporoparietal regions for the ‘Aha! answers’ but not for the ‘No-aha’; the generator of that was again the ACC. A year later Qiu et al (Qiu et al, 2007), using a Chinese character generation task, found that when the provided answer was not what subjects initially guessed (‘unexpected correct answer’), a N320 component was produced in comparison with answers that were consistent with subjects solutions (‘consistent answers’). The N320 was larger at the midline parietal electrode and generated at the ACC. ‘Unexpected correct answers’ also evoked a

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<sup>8</sup> Chinese logogriphs are “riddles in which writing characters undergo several changes brought about by the addition, subtraction, omission or substitution of strokes or components of the characters” and “the solution may be obtained either by restructuring the components of the characters to make new ones or by discerning the riddles’ implicit meanings.” Qiu et al., 2006

<sup>9</sup> Dipole analysis is the method used to identify the possible location that generates the brain impulse by using machine-learning algorithms

positive deflection at the parieto-occipital region at the time window of 500ms - 600ms at the posterior cingulate cortex (PCC). Authors suggested that this late positive component might be a P3, reflecting the attentional resources employed and its latency indexing the relative duration of stimulus evaluation and classification. The assumption in these studies is that understanding the answer would suddenly break the initial mindset of the superficial meaning of the task (e.g. of the riddle) and that the activation of the ACC might reflect the cognitive conflict between the old and the new mindset.

However, the underlying cognitive process of understanding passively a provided answer is probably different than actively thinking of the solution. Thus, Jiang Qiu and colleagues employed a novel task, the learning-testing paradigm, where they provided heuristic information to be used as a prototype on how to solve the test logogriphs and break the mental set created by its misleading information. In their first study (Qiu & Zhang, 2008) the successful solving of the logogriph, but not recognition of the solution of the prototype logogriph, elicited a negative deflection (N350) at 300ms- 350ms over the front-central area and a later positive component (600ms-700ms post-stimulus) in frontal regions. According to the dipole analysis the negative deflection was generated in the posterior cingulate cortex (PCC) and inferior frontal gyrus and the positive component in the right parahippocampal gyrus. The researchers' hypothesis is that the negative wave might reflect inhibitory processes of the superficial meaning of the logogriphs and the late positive component might be a P3-like, indicating evaluation and classification operations, the search of the correct answer and recovery of verbal information. Findings from their subsequent study revealed a more positive wave at parieto-occipital electrodes (in time window 200ms - 600ms) for 'successful guessed' logogriphs Vs 'unsuccessful', generated at the left Superior Temporal Gyrus (Qiu et al, 2008). They hypothesized that it may be a P3 component reflecting heuristic information retrieval and memory updating. In addition, the ERP waveform elicited a negative slow wave N1500-2000 at left frontal scalp generated at ACC, reflecting cognitive control in 'breaking' the superficial meaning of the logogriph and N2000-2500 at parietal, temporal and occipital areas (generated at PCC).

Even though the solution in the above learning-testing paradigm is internally generated, the solver needs to associate his knowledge from prior experience (the learning state) with the new problem at hand, whereas insight solutions are described as moments where the sudden learning occurs by breaking the mental set, the assumption caused by previous experience. Breaking the mental set implies breaking “the tendency to solve certain problems in a fixed way based on previous solutions to similar problems”(Zhao et al, 2011). Zhao and colleagues 2011 used again the learning-testing paradigm but in a different way. Subjects were provided with heuristic information on how to solve a Chinese character generation task in order to be biased into a mental fixation produced by this prior experience. However, later, during the test-stage, a restructuring of this prefixed mental set was required in order for subjects to find the solution. The ERPs of the ‘breaking mental set’ condition, elicited a more positive deflection at centroparietal regions (300ms–500ms) probably reflecting attentional resources employed when realizing the unsuitable mental fixation and a later positive slow wave (900ms-1300ms) in the same area that, according to the authors, is probably associated with searching and generating the novel adequate character after breaking the mental set. Another group of researches, again focusing on the active process of restructuring, compared the ERPs of insight logogriph problems Vs routine problems (Wang et al, 2009). At the time window of 300ms-800ms post-stimulus, they found a negative deflection at frontocentral areas, originate at the ACC reflective “the effort of conscious inhibition of the superficial meaning” and a positive one at parieto-occipital channels, from activity in the parahippocampal gyrus, associated with stimulus evaluation and memory updating. A later positive slow wave, at 1200ms to 1500ms, at the same regions was associated with the formation of the ‘novel conjunctive representation’ whereas the negative slow wave at the same window in frontocentral areas, reflected conflict resolution and was generated, according to dipole analysis, at the superior temporal gyrus (ibid.).

Finally, a different experimental task, that does not involve verbal semantic associations, was employed by Lang et al. (2006) in order to investigate insight as a process of transition from implicit to explicit reportable knowledge. They used the number reduction task (NRT), which involves a sequence of 6 digits that needs to be transformed into a new sequence based on the predefined rules in order to reach to

the final result. In the new generated sequence there is a certain underlying regularity: the final 2 pairs of digits are mirrored e.g 19449, 43993. When subjects gain insights into this hidden regularity their reaction times drop significantly. Researchers found a larger slow positive wave, for solvers who gain insights versus non-solvers, at the parietal region between 200ms -1200ms after the presentation of the first digit. They hypothesized that these larger amplitudes might be related to short and long-term memory processes and that solvers were storing the perceived events into their memory to a greater extent.

The conclusion from the review of the studies on insight is that the ERP findings do not appear to have strong consistency in terms of components, latency, and scalp distribution. That is probably due to methodological issues (actively and passively induced insights, or prototype induced insights), to the variability of experimental tasks employed (Chinese character generation, logogriphs, puzzles, riddles) as well as the different control conditions -the ‘No-aha’ conditions- that have been used (easy riddles, routine problems, recognition, unsuccessful solution, solutions without impasses). These different experimental manipulations might elicit different cognitive processes which might be the cause of the inconsistencies observed in the reviews (Dietrich & Kanso, 2010; Shen et al, 2013b). Although these studies are excellent attempts to identify the neural activity of insights, further work needs to be done particularly regarding the experimental paradigms employed to investigate insights. Additionally, the compound remote association task which is mainly based on verbal fluency and lexical relations might be related to the “concept integration ability”, rather than a problem-solving ability (Qiu et al, 2008). Several authors highlight that externally triggered insights with hints and training interventions may involve different cognitive processes than an internally generated solution (Ash et al, 2012; Luo & Knoblich, 2007; Qiu et al, 2008).

However, the ERP data presented here show a certain pattern with two main components: most of the studies have reported a front-central negative deflection generated at the ACC and a positive wave, a P3- like component, at the parietal-occipital electrodes caused by the activity of the parahippocampal gyrus. The anterior cingulate cortex, as mentioned earlier, is thought to be important in detecting the cognitive conflict and initializing the breaking of the mental set. The

parahippocampal gyrus and hippocampus along with adjacent temporal regions are mainly responsible for the formation of novel associations, according to Shen's et al review (Shen et al, 2013b). The initial focus of the ERP research on insight was on the negative deflection produced at the ACC. There were several attempts to explore further the N380 component (or N320, N350 in other studies) since the initial hypothesis was that this might be the 'Aha! effect' (Luo et al, 2004b). However, in the study by Qiu and colleagues (2006), this early signal of conflict was observed not only in the ERP waveform of the 'Aha! answer' but for 'Uncomprehended answers' as well. That means when participants could not understand the provided correct answer, the same conflict response was present although it did not lead to a deeper understanding of the problem nor to the Aha! experience.

Therefore, the ACC activity is not sufficient to elicit the successful restructuring of the mental representation. Although the ACC mediates this process, the shift of the problem representation depends on a 'non-linguistic' processing network (Qiu et al, 2008). According to Shen and colleagues (2013b), "the effective transformation of problem representation depends on a non-verbal visuospatial information-processing network that comprises the precuneus and cuneus and other regions that are distributed in the parieto-occipital junction". The authors also provide additional evidence that the activity of the parietal lobe and nearby areas is related to the restructuring of the presentation. They refer to two fMRI studies on sequential learning where insights -that is the acquisition of explicit knowledge on the implicit rule- was associated with activation in the precuneus and cuneus and they propose that these adjacent regions of the parietal lobe are involved in a visuospatial information processing network and memory retrieval (ibid.).

A similar parietal positivity has been also observed in studies of ambiguous images where the perception of the stimulus changes suddenly while the stimulus itself stays the same. A recent paper on ambiguous figures, mentions several studies on such insight-like phenomena in visual perception, like the Necker cube or the Old/Young woman image (Kornmeier & Bach, 2012). The authors suggest that the perception of ambiguous figures and insights share a similar underlying process, which involves passing from a transient state of maximal instability and conflict to a state of disambiguation. They mention two studies where a positive component was

observed at the time window of -500ms to -200ms before key press indicating the conscious recognition of a perceptual switch. This parietal positivity (often following a frontal positivity) has been interpreted again as a variant of the cognitive P3 component. The P3 was observed when using the onset of a stimulus as time reference as well when using manual responses (Kornmeier & Bach, 2012). Consequently, the positive parietal P3-like component reported in most of the ERP studies focusing on insights and in perceptual switch of ambiguous images is highly likely to reflect the moment of the representational change. The next paragraphs, therefore, are focused on this event-related component, the oddball paradigm that has been traditionally related to the P3 and on the time-frequency components associated with this neural response.

The P300 or P3 is a well-studied event-related potential (ERP) component. It has two subcomponents: the P3b, with origins in the temporal-parietal junction, and the frontal P3a (Patel & Azzam, 2005). These two subcomponents, the P3a, and the P3b are usually observed at the frontal/central and parietal regions respectively. Experiments using the oddball paradigm, report that the P3a and P3b are associated with different stimuli categories. For example, both subcomponents are observed in the three-stimuli oddball paradigm where a sequence of standard frequent stimuli is presented and is interrupted by infrequent target stimuli (10%-20% of the cases) and novel non-target ones. The P3a or novelty P3 is a frontal response to unpredictable/novel, non-target stimuli. The P3b is related to unexpected events that are task-related (target) and its amplitude gets larger as the probability of the task-related event gets smaller (Luck 2005). Additionally, the brain's response to target stimuli in oddball experiments correlates negatively with age, that is the component's amplitude decreases and latency increases (Polich, 2012).

The P3 signals the occurrence of a deviation from what is expected and its relation to the hippocampal system is not unreasonable since the hippocampus seems to be sensitive to the probabilistic context in which events occur (Harrison et al, 2006).<sup>10</sup>

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<sup>10</sup> An interconnected network that includes the left hippocampus, bilateral parieto-occipital sulcus, left retrosplenial cortex and right anterior cingulate has been reported to be involved in "*learning contextual relationships engendered by conditional dependence among consecutive events*" within a sequential reaction time task (Harrison et al., 2006).

Additionally, larger P3 amplitude is observed over the right compared to the left frontal/central areas in the oddball task, which is reasonable given a “frontal-parietal right hemisphere attentional network system” (Polich, 2012). The frontal/central P3a component has been associated with orienting response to novel and deviant stimuli (novelty detection). The P3a reflects an attention-related process and originates from a representational change in the working memory caused by novel and deviant stimuli. The P3b occurs when “the attention-driven stimulus signal is transmitted to temporal and parietal structures” (Polich, 2012, p.180). The P3b is related to context updating mechanisms and memory operations that are triggered by novelty detection mechanisms as reflected by the P3a.

Several studies using time-frequency analysis of the frontal P3a and parietal P3b have reported associations with theta, delta and alpha components. Studies investigating time-frequency components in relation to the P300 (in the oddball task) have reported increased frontal theta-band (4-8Hz) activity (Mazaheri & Picton, 2005) with a simultaneous delta component for rare/target stimuli as well as widespread alpha-band (8-12Hz) desynchronization reflecting increased attention to detect infrequent stimuli (Peng et al, 2015). Event-related theta activity was found to be increased in amplitude for novel stimuli relative to constant non-target stimuli and novelty effects were also found to affect alpha frequency components (Demiralp et al, 2001). In a wavelet analysis of the P300's subcomponents, two theta frequency components were associated with the novelty detection mechanism: an early component suggesting occipital parietal generators “leading to a bilateral posterior positivity and a midline frontal-central negativity” and a later one with right temporal-to-frontal distribution suggested to “reflect a hippocampal-temporo-frontal network that is reacting to rare events deviating from the stimulus context” (Demiralp et al, 2001).

Frontocentral theta (3-7Hz), in the oddball task, has been related to “narrow salience processing”, reflecting attention and orienting processes, and delta (<3Hz) was associated with more sustained complex-stimulus processing and evaluation. The frontocentral theta response has been reported to “scale relative to any attentional demands” and was larger for P3a (Bachman & Bernat, 2018). Other findings suggest that difficulty in discrimination of stimuli, rather than the level of novelty, seems to



determine the P3a generation but “the underlying theta oscillations are differentially affected by stimulus novelty” (Demiralp et al, 2001). The P3b parietal component has been associated with alpha power decrease (Polich, 2007). Alpha posterior power decrease for visual targets has been associated with perceptual processing, context-updating, and maintenance of working memory (Mazaheri & Picton, 2005). Higher magnitude of alpha power decrease (8-13Hz) for targets vs. non-targets was observed for several modalities, using, for example, auditory or visual oddball stimuli (Peng et al, 2012).

According to the Context-Updating hypothesis developed by Donchin (Donchin, 1981), the P3 is associated with the updating of the mental representation of one's current environment, to incorporate the new unexpected but task-related information. He suggests that “events are remembered if they require, upon their occurrence, a restructuring of our mental models which is presumably what happens when we are surprised” and he comments that “it is conceivable that these are the processes that are manifested by the P300”. Therefore, variants of the P3 component in studies of insight can be considered as indexes of the representational change and sudden updating of the mental representation. The P3 component and the related time-frequency components (frontocentral theta and posterior alpha power responses) along with the consistent finding of alpha power decrease in EEG studies on insights (Dietrich & Kanso, 2010) set the initial prediction for what might be the brain's response to the representational change and the Aha! experience.

## 2.2 The Moment of Spatial Re-orientation

To orient ourselves during navigation, we must be able to recognize our surroundings, use stable environmental landmarks to make decisions and maintain our orientation while keeping track of our movement. Dudchenko explores the psychology and neuroscience of navigation, in his book called “Why people get lost”, to understand how we find our way and how our own brain may mislead us. Losing spatial orientation may be a result of misorientation or disorientation. Under some circumstances, our sense of direction may become ‘turned around’. Evidence from rat experiments shows that the sense of direction relies on an orienting mechanism, which is based on the integration of the internal sense of movement and information from head direction cells. These are specific neural cells that fire if the heading is oriented in a certain direction (Dudchenko, 2010). Head direction cells are insensitive to gradual changes and may fail in some cases to detect changes in our direction of movement. This can cause a sense of direction that is misleading. Misorientation can be caused by an incorrect orientation of grid cell fields from inputs of head direction cells. We may come out of the tube, heading confidently towards one direction only to realize suddenly, after walking for a while, that we are actually going to the opposite direction. The reason is that we are passively displaced and the updating of our orientation, based on self-movement and vestibular cues is disrupted. In cases like these, we are misoriented; that is our “sense of direction is no longer anchored to the external world” and “the directional system may provide an incomplete updated orientation or display a new orientation” (Dudchenko, 2010, p.253-254).

Disorientation is the failure of self-localization where “grid and border cells become unstable” (Dudchenko, 2010). Disorientation causes a switch from the use of a temporary, egocentric representation of space to a more stable representation of relations between landmark-locations (Waller & Hodgson, 2006). Information from an allocentric representation is then used to update our egocentric representation and change our course of action (Basten et al, 2012). And as Burgess comments: “action-oriented egocentric representations must be derived from enduring allocentric representations following long or complicated self-motion” (Burgess, 2006). A recent review on the neurocognitive basis of spatial re-orientation supports the idea

that re-orientation processes are initiated when spatial updating (either egocentric and/or allocentric) is disrupted and that this causes a shift towards allocentric representation to re-establish one's spatial coordinates (Julian et al, 2018). Reorientation after disorientation depends greatly on the spatial information of the immediate environment (Meilinger & Vosgerau, 2010) which facilitates self-localisation. Sudden reorientation, therefore, shares significant similarities with insightful problem solving: the experience of impasses of disorientation or misorientation, restructuring of the misleading 'turned around' heading, deeper understanding of one's actual location and orientation and the Aha! experience of reorientation.

The process of re-orientation involves two major components: the recovery of the appropriate reference frame to establish one's location and the recovery of the correct heading in relation to that reference frame (Julian et al, 2018). Laboratory experiments indicate that the geometry of the environment (e.g. environmental shape) acts as a strong cue for re-orientation. Also, tasks that involve processes similar to that of re-orientation, such as the judgment of relative direction task ('Imagine you are at the X, facing the Y. Point to Z'), show that there is a preferred direction from which participants performed better. In terms of egocentric representations, this is the initial viewpoint during learning. This direction is especially strong in preference if it is aligned with the intrinsic spatial organisation of the environment (e.g. local geometry, spatial axes, intrinsic alignment of object or arrangement within a room). The environment provides strong cues for the recovery of the reference frame even if the current view is not aligned with the viewpoint during learning (ibid.).

This section provides a review of the neural mechanisms that support navigation and orientation exploring the characteristics of place, grid, head direction and boundary cells in the hippocampal formation and their relation to the environmental information (e.g. geometry, boundaries, landmarks). The processing of the environmental input, that facilitates reorientation, is supported as well by certain brain areas that are sensitive to information in visual scenes. These are the retrosplenial cortex, occipital place area and parahippocampal place area, which are also discussed in this chapter. The literature review discusses aspects of spatial

memory such as encoding and retrieval of episodic memories and theories that focus on how we move from context-dependent episodic memories to context-free semantic memories or higher-order structures. Finally, a summary of relevant electrophysiological studies is provided which points towards the pattern of brain dynamics that is assumed to reflect the Aha! experience of spatial re-orientation.

### **2.2.1 Neural Mechanism Supporting Navigation and Orientation**

The ability to keep track of our current position in relation to environmental cues and stay oriented within the immediate environment is called *spatial updating* (Wang & Brockmole, 2003). Spatial updating involves an ‘intuitive’ ability of self-localization, a ‘you are here’ internal sign. As we move within the environment we perceive the sensory information of the world as relatively stable even though the sensory input changes rapidly with our movement. The two sources of information, that is of self-movement and of environmental input, contribute to processes of self-location (Barry & Burgess, 2014). Information related to self-motion is updated by motor systems, idiothetic information from vestibular inputs (reflecting acceleration) and proprioceptive cues -signalling changes in direction and location and supporting thus path integration mechanism- and optic flow, even though the latter is not necessary for spatial updating based on egocentric movement (Barry & Burgess, 2014; Burgess, 2008; Byrne et al, 2007). The sensory perception of the environment (environmental information) supports the updating of the individual’s location in relation to environmental features or objects. Path integration refers to the updating of the representation of one’s displacement from the point of origin of movement based on these two sources of complementary information (Burgess, 2008). Spatial updating and path integration are usually considered as egocentric processes (ibid.). However, Burgess (2008) notes that the update of the representations depends “on whether the object or start locations are updated relative to the participant or whether the location of the participant is updated relative to the locations of objects, start positions or other aspects of the environment”. For example, over longer distances and after a small number of turns path integration and spatial updating of egocentric representations become unreliable (ibid.). In these cases, the spatial updating of allothetic information rather relies on allocentric representations (Burgess, 2008; Byrne et al, 2007).

The brain provides the ‘you are here’ information through a set of neurons called ‘place cells’. In 1971, John O’Keefe and colleagues conducted electrophysiological recordings of individual neurons, within the hippocampus and reported that certain neurons show maximum firing when the rat’s head was in a specific location in the environment, regardless the way is facing, while a different set of neuronal cells were activated when the rat was in a different location (Keefe & Dostrovsky, 1971). The area where a high firing rate for a certain place cell is observed is called the cell’s ‘place field’. John O’Keefe was awarded the Nobel Prize for Physiology or Medicine in 2014 jointly with May-Britt Moser and Edvard Moser for the discovery of place and grid cells respectively; the “cells that constitute the brain’s positioning system”. John O’Keefe and Lynn Nadel reviewed studies on rats with lesions in the hippocampus and along with the discovery of place cells, they concluded that these cells form the neural bases of spatial cognition (Keefe & Nadel, 1978). Furthermore, they argued that the function of hippocampus provides the substrate for the construction of a mental representation of the spatial environment, which they called a ‘cognitive map’, borrowing a concept that was first introduced by Edward Tolman in (1948).

Place cells are established on the first exposure to an unfamiliar environment and they increase their firings in familiar environments whenever the animal passes the area of their place field (Barry & Burgess, 2014). Different place cells have different place fields and thus the animal’s current location is represented accurately by a small population of cells (Hartley et al, 2014). In different environments, place cells have distinct firing patterns and place fields, which are relative to environmental features. This process is known as ‘remapping’ (Barry & Burgess, 2014) and results in representing every environment in a unique way. In familiar environments, a change in some environmental cues does not affect their firing patterns. However, removing more important cues such as an environmental boundary (e.g. a wall) will cause remapping (Hartley et al, 2014).

The neural representation of location is supported by representations of orientation. Head direction cells -found in a network of areas including the presubiculum, the thalamic nuclei, and entorhinal cortex- provide an allocentric heading representation that is independent of location (Hartley et al, 2014). The rate of firing of each cell

increases whenever the animal's head faces towards the preferred direction and the relation between the preferred firing direction of the cells (angular offset) remains constant across environments (Barry & Burgess, 2014; Hartley et al, 2014). The head direction cells thus contribute to an internal sense of direction. Place cells rely on these cells for directional information since cue manipulation in relatively simple environments (e.g. removing the single cue card a circular arena) disrupts both cell-types' orientation firing that was jointly aligned by the direction of the card (Barry & Burgess, 2014).

Another type of spatial cells that contribute to the allocentric representations, which are again independent of the animals facing direction, is the grid cells (Herweg & Kahana, 2018). They are found in the entorhinal cortex (and pre and parasubiculum) and fire at a specific location in the environment with a regular triangular pattern (Hartley et al, 2014). In 2005, research by a group led by May-Britt Moser and Edvard Moser (Hafting et al. 2005 in Hartley et al., 2014) confirmed the existence of grid-cells in humans, firing "at the vertices of a hexagonal grid" across the environment (Hartley et al, 2014; Herweg & Kahana, 2018). A subset of neighbouring grid cells shares the same orientation of the grid axes and scale, but cells within different groups act independently and respond in a different way to changes in the environment (Barry & Burgess, 2014; Hartley et al, 2014). Also, the spacing of their pattern (distance between neighbouring firing peaks) seems to be a function of environmental size and is coarser for larger environments (Herweg & Kahana, 2018). Researches support the view that grid cells serve path integration and are important for place cells' function only when external sensory information is weak (Hartley et al, 2014).

In contrast, border /boundary vector cells, respond to distance and allocentric direction from an environmental boundary and most likely shape the spatial response pattern of place cells (Byrne et al, 2007). Manipulations of environmental geometry influence the spatial tuning of place cells which tend to be determined by distances to the boundaries of the environment such as the nearest wall (Hartley et al, 2014). Distinct landmarks within an environment, on the contrary, have a weak effect on place cell's firing (Burgess, 2008). These cells project to the hippocampus (Byrne et al, 2007) and boundary vector cells respond to both vertical surfaces and drop edges

(Hartley et al, 2014) that essentially describe environmental boundaries. The functions of border/boundary cells suggest that environmental geometry is an “important sources of external sensory information supporting cognitive mapping in the hippocampal formation” and apart from their contribution to place cell firing they might be related to grid cells as well (ibid.). One assumption is that boundary cells initially drive the shape and location of place fields and then grid cells are anchored in turn in relation to place cells’ firing. Alternatively, boundary vector cells may anchor grid cells directly to the boundaries of the external environment. The second alternative seems more aligned with the idea that environmental boundaries may provide “a valuable error-correction mechanism” for path integration which is related to grid cells (Barry & Burgess, 2014).

Another important property of place-cells is that in one-dimensional navigation (e.g. linear tracks or arms of a radial maze) they exhibit unidirectional firings. That is, they tend to be direction-specific; their synaptic connections are strengthened towards the forward direction but not backward (Buzsaki, 2005; Byrne et al, 2007). In open environment, however, or where the specific area has *place-unique cues* (e.g. at the centre of the radial maze) the place cells appear to be omnidirectional (same firing rate for different directions) forming time-independent associations (Buzsaki, 2005; Herweg & Kahana, 2018). Hartley and colleagues’ comment that the place cell’s omnidirectionality is dependent on intact head direction cell’s input since lesions in the rat’s head direction system cause place fields to become more directional. They conclude that the allocentric map-like quality of hippocampal representations probably depends on the function of intact head direction cells (Herweg & Kahana, 2018).

Recordings of place cells in rodents show that distant visual features have a strong effect on the orientation of the hippocampal map. However, Julian and colleagues (2018) argue that these findings come from studies on oriented animals and that these features located at the extremities of the environment, may be used for re-orientation if they were previously experienced as stable while the animal was oriented. On the contrary, studies on disoriented animals show that the response of hippocampal place cells, head-direction, and grid cells tend to be controlled by the environmental geometry after disorientation (ibid). However, it is important to

mention here that there are also evidence that support the idea that “remapping” of grid cell, which is the translation and/or rotation of their fields in response to environmental change, was only observed in response to large environmental changes (animals moved to a new room) as opposed to small changes (Jeffery, 2011). Also, the system of head-direction cells often conceptualized as a 'neural compass' is not only sensitive to the environment shape but also to non-geometric cues that “take the form of a constellation of multiple objects” (ibid).

Therefore, the hippocampal system supports re-orientation by providing detailed representations of location and heading direction based on inputs from spatial cells including place cells, grid cells, head direction cells, and border/ boundary cells. Inputs from head direction cells to place cells via border cells might contribute to the reorientation of the cognitive map (Julian et al, 2018). The environmental geometry appears to have a strong influence on these representations and the ‘sense of direction’ derives from a network that includes head direction cells. Head direction cells contribute to place cells’ omnidirectional firing which is associated with place-unique cues.

### **Spatial mental representations and their coordinate transformation**

Neuroscientific studies on spatial memory suggest that the representation of spatial information occurs at two different interrelated neural networks that correspond to the two reference frames. The translation from one network, or reference frame, to the other requires information from the head direction cells which are responsible for the orientation of the observer. Spatial reference frames are usually divided into two categories: the egocentric and allocentric (Klatzky, 1998). The egocentric is an action-related reference frame, which represents self-to-object relations and the specific orientation and location of the observer. An individual body-centred vector represents each different location. Whereas the allocentric is an orientation-free reference frame and encodes object-to-object relations. Allocentric reference frames are external to the body and derive from a global environmental layout (Meilinger & Vosgerau, 2010).



Burgess (2006) argues that spatial updating can be seen as a two-system model of a continuous translation between egocentric and allocentric representations. According to this model, transient egocentric representations, generated in the parietal window (posterior parietal cortex and precuneus), are recruited in short-term spatial memory for immediate action and mental imagery. Coarse allocentric representations that are supported by information stored in long-term memory are generated in the hippocampus and surrounding medial temporal lobe areas. Encoding and retrieval of information require a translation between the two representational systems.

Humans represent spatial relations using both coordinate systems, which may be often combined in pair-wise or hierarchical relations forming more complex spatial representations (Meilinger & Vosgerau, 2010). However, individuals may rely more on a certain reference frame depending on the circumstances (Mou & McNamara, 2002) or individual differences (Gramann, 2005). For instance, several researchers suggest that spatial memories of small layouts are represented in terms of egocentric reference systems while the lack of influence of movement-related spatial updating in large-scale navigation, implies the use of a more stable allocentric system (Burgess, 2006). Gramann and colleagues (2005) investigate individual differences using a point-to-origin task which allows the categorization of subjects into turners and non-turners based on their preference for using an egocentric or an allocentric reference frame respectively. For turners, the perceptual heading seems to be updated during movement, but the strategy used by non-turners often results in a misalignment between the perceptual and cognitive heading (Gramann, 2005). The reliability of the effect is confirmed by a virtual reality experiment on path integration (Riecke, 2012). In this study, path integration was based only on optic flow in order to disassociate piloting (spatial updating from landmarks) and path integration. According to the researchers, longer response times to the pointing task for non-turner implies the use of an offline ‘after-the-fact’ cognitively demanding strategies such as mental rotations or abstract geometric strategies. While turners seem to rely on an online updating strategy with the help of an imagined homing vector (*ibid.*). An EEG study investigating the impact of path complexity of virtual tunnel passages on path integration for turners and non-turners has reported different neural circuits associated with each case. Egocentric representations seem to be computed along the dorsal pathway involving the medial occipital and posterior

parietal cortex while allocentric representations are computed along the ventral pathway, which involves, among other areas, the hippocampal structure (Plank et al, 2010).

According to Burgess these two circuits are activated in parallel and involve areas that process the spatial information in a reference-frame-specific manner but also areas that are responsible for the “coordinate transformation of spatial information between the two reference frames” (Burgess, 2006). Research focusing on the interrelation of allocentric and egocentric reference frames suggests that data from the perception-action format are translated into egocentric representations and with the integration of head direction cells result in the hippocampal place cells. At the same time, the retrieval of elementary spatial representations is necessary to guide action and “the coordinate system representing spatial relations in memory has to be transformed into the current egocentric coordinate system to elicit behaviours” (Meilinger & Vosgerau, 2010). This coordinate transformation is usually studied in alignment experiments where there is a misalignment between the current orientation and that of the egocentric or allocentric memory representation. Spatial representations stored in memory are viewpoint-dependent (Avraamides et al, 2012; Basten et al, 2012; Meilinger & Vosgerau, 2010), and when there is a misalignment with the current heading “a differently oriented egocentric or allocentric memory requires a coordinate transformation into the current egocentric orientation” (Meilinger and Vosgerau, 2010).

The two-system-model also implies that we operate on distinct representations over different timescales, for example in small and large scale environments (Burgess, 2006). Wang and Brockmole’s experiment (2003) is one example that involves such transformation and integration of distinct representations. Blindfolded subjects were asked to point to objects inside the room and outside locations of the campus. When participant’s heading was aligned with indoor objects they were faster at pointing to other indoor location than to campus landmarks but when their viewpoint was aligned with outdoor locations they were equally fast. The main conclusion was that the representation of the campus included that of the room but not the other way around. When oriented in relation to the immediate environment (room), switching to a large-scale representation of the surrounding environment is cognitively

demanding because it involves the transformation of allocentric information and updating of one's current egocentric representation (ibid.).

Waller and Hodgson's (2006) disorientation paradigm provides evidence for the two-system theory. In their experiment subjects first learned the locations of objects positioned in a room. Participants then entered a rectangular opaque chamber in the middle of the room and sat on a rotating stool. They were asked to point to different objects in the room and conduct a judgment of relative direction (JRD). Their performance was tested with eyes-open, eyes-closed and after rotating the stool they were sitting on, which caused a certain degree of disorientation. The main finding of this study is that after disorientation variability in errors increased in the egocentric pointing task and decreased in the allocentric JRD task. This suggests that disorientation causes a switch from the use of a temporary, egocentric representation of space to a more stable allocentric representation of spatial relations.

### **2.2.2 Brain Regions Contributing to Orientation**

The literature suggests that there are certain regions in the brain that facilitate context recognition and have a strong response when navigationally-relevant visual stimuli are presented (Figure 2.2-1). These are the retrosplenial complex (RSC) encoding information about location and direction and is significantly involved in spatial processing, the occipital place area (OPA) which is related to boundary-relevant information processing and navigational affordances and may have a special role in recovering position and the parahippocampal place area (PPA) involve in context and place recognition (Hartley et al, 2014; Julian et al, 2018). These regions have a complementary role in the function of the hippocampus and are suggested to play an important role in orientation and re-orientation (ibid.).

The involvement of the retrosplenial complex in spatial re-orientation is supported by findings from lesion studies. For example, lesions in this area cause 'heading disorientation' which results in "an inability to use perceptual information to orient" in large scale environments (Julian et al, 2018). Additionally, these lesions cause impairments in tasks that require the transformation between spatial frames of reference (Julian et al, 2018). The integration of egocentric information into allocentric representation is thought to rely on the retrosplenial complex, and alpha

power decrease observed in orientation studies has been associated with this area (Lin et al, 2015).

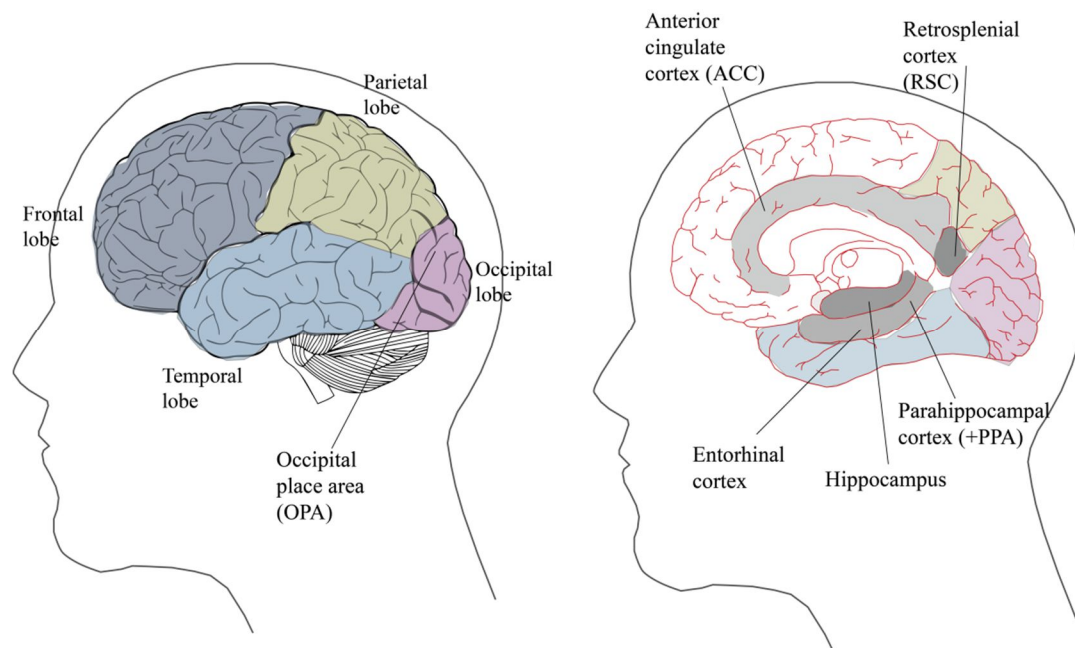


Figure 2.2-1. Brain's anatomy and main regions that contribute to re-orientation. A visual summary of the relevant literature review.

Support for the role of this region in reorientation comes from an fMRI study which provides evidence that location and direction are represented in the retrosplenial complex and are coded in relation to a reference frame that is anchored to environmental features of local geometry (Marchette et al, 2015). The authors used a virtual reality environment with several rectangular ‘museums’ occupying a large courtyard. The participants learned the locations of objects within the museums and then asked to perform a judgment of relative direction from several imagined locations and facing directions. The researchers observed greater pattern similarity in the fMRI results (multi-voxel pattern analysis) for same-direction views (e.g. facing along the long axis of the museum) and/or views obtained from the same location. Interestingly, an accurate map of spatial relations between the views could be recreated based on the pattern of these neural codes in the retrosplenial complex (ibid.). The authors observed that alignment principles in relation to the local geometry (i.e. the local north with a heading direction to the back wall) were the same across the different ‘museum’ buildings and noted that:

A geometry-dependent but environment-independent representation of this type might be critical for translating viewpoint-dependent scene information ('I am in a rectangular room, facing the short wall') into allocentric spatial codes ('I am facing to the North')—and, conversely, for re-creating viewpoint-dependent scenes from allocentric memory traces. (Marchette et al, 2015).

Inputs related to perceptual information of the local environment and the scene's spatial structure are suggested to rely on the activity of the occipital place area (OPA) (Julian et al, 2018). Occipital place area (OPA) appears to be associated with the perceptual input of geometric/boundary information in visual scenes (ibid.). Julian and colleagues (2016) used a virtual reality memory task and transcranial magnetic stimulation to examine this assumption. In this task, participants had to learn locations of objects within a virtual reality environment enriched with landmarks that were moved to different locations during the test phase. Participants appeared at random locations and had to identify objects' locations. Some objects were fixed in relation to landmarks and others in relation to boundaries. The researchers reported that interruption of processing of the right OPA, with the use of transcranial magnetic stimulation, impairs spatial memory for objects encoded in relation to the boundary but not for objects encoded in relation to landmarks (Julian et al, 2016). This area has also been associated with the coding of navigational affordances (Bonner & Epstein, 2017). In this study, navigational affordances in visual scenes (such as locations and number of visible exits) were systematically manipulated while other visual properties remained constant. The findings suggest that activity in the OPA shows sensitivity to the differences in the spatial features of visible exits even if the scene has the same geometric shape (ibid.). Navigationally related boundaries, as opposed to navigational affordances, indicate where one's movement is blocked and thus these two characteristics of the activity of the OPA appear to be complementary (Julian et al, 2018).

Parahippocampal place area (PPA) is involved in providing context information (Julian et al, 2018; Park et al, 2011). It is of great interest because it is also involved in recognition. Lesions in this area cause impairments in place recognition ('landmark agnosia') and the PPA seems to respond to objects that have properties

that would make them useful as landmarks such as stability, large size, and visibility from distance (Julian et al, 2018). Also, it seems to represent the gross shape of space as defined by boundaries, such as open vs. closed (ibid.). It has been suggested that this area informs the hippocampus about the context of navigation and contributes to context/ place recognition based on a variety of cues.

Earlier research suggests that the PPA is sensitive to the perceptual aspects of the stimulus while more recent experiments have found that the area responds to visuospatial discontinuities such as edges, corners, borders, and other spatial details. For example, the PPA response differently to a cube stimulus that has distinct spatial discontinuities such as edges and 3D corners (high spatial frequency) in relation to a sphere, even if surface operations (e.g. bumpy surface) were applied to both objects (Rajimehr et al, 2011). The researchers also discuss whether the notion of 'placeness' of a certain location could be quantitatively related to the property of spatial frequency (ibid.).

Another study suggests that “the PPA and RSC play distinct but complementary roles in place recognition” (Epstein et al, 2007). The study used a location, orientation, and familiarity task conditions on images of a college campus and the results showed that RSC had a stronger response to images of the familiar campus than to an unfamiliar campus but not the PPA. Activity of the RSC, but not of PPA, was also associated with the location retrieval task. The researchers report that it is likely that the PPA supports mainly perception of the immediate scene, while the RSC may support memory retrieval mechanisms which permit the localisation of the scene within the broader spatial environment (Epstein et al, 2007). Hartley and colleagues (2014) comment that a network of areas that include the RSC and PPA and are centred on the hippocampus, may be also involved in spatial imagery such as retrieving episodic memories, imagining novel events or adopting another person's perspective and may have a “more general ‘self-projection’ or ‘scene construction’ function” (Hartley et al, 2014). Within this network that facilitates episodic memory and prospective thought it is possible that “by situating our imagined position and heading relative to stable spatial reference elements, RSC allows us to mentally place ourselves within an imaginary world built on the foundations of our remembered experience” (Marchette et al, 2015).

### **Processing of geometric and non-geometric cues**

During wayfinding, landmarks can be used by animals and human as external cues for self-localization and orientation (Epstein & Vass, 2014; Klippel et al, 2010; Klippel & Winter, 2005). Representations of spatial knowledge can be anchored to such entities which are cognitively and perceptually salient (Klippel et al, 2010). Landmark-based piloting is a strategy that is usually used in familiar environments, re-calibrating position and heading, while path-integration is used to update one's position in relation to the starting location and thus more useful when exploring unfamiliar environments. In order for the navigator to re-calibrate her position and heading based on landmark information, she first needs to recognize that landmark. The parahippocampal place area (PPA), involved in landmark and context recognition in general, shows sensitivity to both geometric and non-geometric features of the scene (Epstein & Vass, 2014; Julian et al, 2018). It is possible that this area contributes to binding the visual aspects of the landmark to the navigational relevant spatial features by assigning “a local spatial coordinate frame onto the landmark object” and perhaps by creating a higher-order representation of a landmark “as an abstract indicator of 'place'” (Epstein & Vass, 2014). The retrosplenial complex (RSC), on the other hand, is involved in the process of self-location and orientation within the broader spatial environment, as discussed in the previous paragraphs (Epstein & Vass, 2014; Julian et al, 2018).

Although the geometric features of landmark locations have been found to be strong cues for orientation, the role of non-geometric features -such as visual cues or single discrete landmark objects and buildings- is a matter of debate (Julian et al, 2018). Julian and colleagues (2018) discuss the contribution of geometric and non-geometric cues to the process of re-orientation based on relevant findings from behavioural and cognitive neuroscience studies. The environmental geometry is a significant cue during re-orientation because the environmental shape is essentially a stable feature of the environment and may provide an intrinsic frame of reference and an orientation axis that can be used for re-orientation. In addition, boundary geometry is perceptually salient since it covers a large field of view (ibid.). On the other hand, discrete landmark-objects are useful if they have been previously experienced as being stable while in an oriented state or if they are distal from the

navigator. This explains, their greater effect in large scale environments and according to the authors, they might be more important during re-orientation in natural environments which are more open (ibid.).

### **2.2.3 Encoding and Retrieval of Spatial Information**

Studies on spatial memory usually examine the factors that affect the encoding and retrieval of spatial information and how the neural activity of spatial cells contributes to spatial cognition. The behavioural responses in spatial memory tasks indicate that allocentric representations of location act in parallel with viewpoint-dependent egocentric representations (Burgess, 2006). The representation of location, of place cells, has a strong relationship with the extended boundaries in the environment but the orientation of their firing patterns is determined by distant visual cues, if available (Burgess, 2008). The human brain seems to encode spatial information using several heuristics that aim to anchor objects to a certain location in space and thus minimize the information needed to be stored in memory. Learning and remembering the structure of the environment involves an interpretation of the spatial information on the basis of a spatial reference frame (Shelton & McNamara, 2001). For example, spatial memory paradigms show that the allocentric representation can be organised in relation to the intrinsic spatial structure of the environment (e.g. axes of object arrays), to extended environmental boundaries or in terms of other spatial cues (e.g. vectors to landmarks) and environmental geometry (Burgess, 2006).

Research suggests that knowledge of spatial relations is organized hierarchically into superordinate structures and subordinate clusters (Hommel & Knuf, 2000; McNamara, 1986; Meilinger & Vosgerau, 2010). When learning target locations in a new environment, people tend to group the acquired information into clusters that share similar spatial and non-spatial properties such as functions or semantic relations (places and objects associated with the same action). At the same time, these clusters are also grouped together forming higher-order structures (McNamara, 1986; Tversky, 1981). Therefore, mental spatial representations are not exact map-like copies of the external environment, as the word ‘cognitive maps’ may imply, but rather “integrated and highly organized knowledge structures processed according to cognitive principles” (Klippel et al, 2005).



Navigation in unfamiliar environments involves the processing of information that is perceived sequentially. Thus, learning of such sequences involves encoding the temporal order of events, their similarities and especially their deviations. Encoding and retrieval of spatial information have been associated with theta oscillations (Herweg & Kahana, 2018). It is also possible that theta oscillations establish associations between non-spatial and spatial information (Buzsaki, 2005). Theta oscillations during retrieval and encoding, seem to organize the firing of these cells that “represent temporal context and remembered or imagined serial order information” (Herweg & Kahana, 2018). Herweg and Kahana (2018) discuss that precession of hippocampal cells to the theta rhythm explains two major findings of episodic free recall: the stronger associations between items that had temporal proximity during encoding and stronger associations in the forward direction than backward. These observations are closely related to the properties of unidirectional place cells that are prominent during linear track navigation. The unidirectional and omnidirectional firing of place cells is discussed in more detail towards the end of this section.

Within the built environment, learning is supported by the detection of rules of environmental regularities and by the series of actions performed within space. The detection of such rules permits the individual to predict upcoming events (Rose et al, 2002). Rose and colleagues support the view that this type of learning is rather incidental which as they comment occurs “in the absence of the capability to consciously report what was learned, and therefore has been termed implicit” (ibid.). Adopting an information theory perspective, Harrison and colleagues used a sequential learning task, to investigate how the brain represents ‘sequential predictability’ and reported the involvement of the hippocampal system, the parieto-occipital sulcus, the retrosplenial cortex and the anterior cingulate cortex (Harrison et al, 2006). These areas are also engaged during navigation and the researchers claimed that “the hippocampus is sensitive to novel events that are, by definition, unpredictable. This level of representation is the predictability of, or uncertainty about, events before they occur” (Harrison et al, 2006). A change in the “temporal regularity of successive events” in an environmental context is an important factor that influences how learnable or legible is a certain spatial layout. This ability of the brain to be sensitive to the structure of the sequence of events (and predictability)

serves memory processes of encoding and retrieval of events in relation to their context. This process facilitates memory mechanisms because remembering an item in relation to its neighbouring items within a sequence or an event in relation to its external context appears to be more efficient than remembering each event individually (Burgess et al, 2001).

The hippocampus provides the mechanisms for encoding this sort of context-dependent information of everyday events and supports, as researches claim, “rapid one-shot encoding of events and their context” (Burgess, 2008). It ‘reflects’ the co-occurrence between the representation of an item (non-spatial) and the place cell representation of location (ibid.). Spatial learning, therefore, is not based on associative learning, following rules of trial-and-error, but is assumed to be incidental (ibid.). More specifically, relevant research on spatial memory suggest that boundary-based learning, which is closely associated with the hippocampal formation, depends on incidental learning as opposed to landmark-based learning which is processed by striatal systems and relies on associative reinforcement; that is learning from feedback over multiple trials (Burgess, 2008; Hartley et al, 2014). Burgess (2008) refers to a relevant study that used a virtual reality experiment to examine object-location memory in relation to environmental boundaries and local landmarks (Doeller et al. 2007 in Burgess, 2008). The fMRI results from this experiment showed that activation in the right dorsal striatum, which is more closely related to route-like responses, correlated with learning objects in relation to landmarks whereas and right posterior hippocampal, supporting more flexible navigation, was associated with learning boundary-related objects (Burgess, 2008).

These two different forms of learning supported by the hippocampus and striatal systems are associated with the two major categories of long-term memory: declarative and procedural (Burgess, 2008). Procedural memory that supports habits and learning sequences of movements is related to striatum whereas declarative memory (semantic or episodic) which is long-term reportable and consciously retrievable memory depends on the hippocampus (ibid.). Patients with damage in the hippocampus have difficulties in creating new memories that are related to personally experienced events (Hartley et al, 2014) and have difficulties in spatial orientation and navigation. A well-known case is the famous H.M patient who had

the hippocampal formation surgically removed for treatment of epilepsy and this resulted in not being able to remember the daily events of his life (Tulving, 2002). The surgery caused impairment to his declarative memory, resulting in difficulties in remembering facts and events which correspond to semantic and episodic memory respectively (Hassabis, 2009). However, he was still able to remember and acquire new motor skills and habits and he could remember things that happen at the present for a short period of time unless something interrupted his attention (short-term memory). His case, along with other empirical evidence, is a strong indication that memory relies on multiple brain regions and different systems (ibid.). The last part of this section offers a broader overview of the two categories of declarative memory, episodic and semantic, and the main theories that focus on the role of the hippocampus in memory.

### **Episodic Memory and the Hippocampus**

The hippocampus has a critical role in supporting episodic memories. These are spatial-context specific memories of autobiographical episodes which, during retrieval, have the distinguishing characteristic of “rich contextual information or feelings of ‘reexperiencing’” (Byrne et al, 2007). With a profound interest in the elements of episodic memory, Tulving (Tulving, 2002) was one of the first to suggest that episodic and semantic memories are two different memory systems. The case of K.C, a patient who had brain lesions in multiple brain regions including medial temporal lobes, is used as an example that supports the idea of these two separate memory systems (ibid.). Due to his injury, he was not able to “to imagine his future any more that he [could] remember his past” but he could “learn new factual information in the total absence of any episodic remembering” (ibid.). According to Tulving (2002) “episodic memory evolved out of semantic memory” and that “its operations require, but go beyond the semantic memory system”. Episodic memory allows an individual to re-experience past personal events and includes recollection of information about the spatiotemporal context and the content of the experience. On the other hand, semantic memory is a context-free memory of factual knowledge (ibid.). It is related with knowledge of categories, concepts, word meanings and can be “acquired during an experience, or across experiences” and “then becomes separated from the specific context of the learning event itself”

(Hassabis, 2009). However, as Tulving (2002) mentions, it is difficult to distinguish episodic and semantic memory by using different laboratory memory task because there is no clear one-to-one correspondence of task to systems. In addition, there seems to be a debate whether episodic and semantic memory “are similarly reliant on the hippocampus” along with an ongoing discussion, within the field, regarding the nature of the representations that are supported by the hippocampus (Hassabis, 2009).

Two of the most influential theories that refer to the relation of the hippocampal representations to memory are the cognitive map theory (O' Keefe & Nadel, 1978) and the relational theory (Eichenbaum et al, 1999). Since the discovery of place cells the involvement of the hippocampus has been traditionally associated with aspects of navigation and spatial memory and the creation of a cognitive map (O' Keefe & Nadel, 1978). The cognitive map theory supports the idea that the function of the hippocampus is primarily to construct and sustain allocentric representation of the environment. The role of the hippocampus, in this case, is to enable associations of location and other elements of experience in memory-structures (Hassabis, 2009). It provides the spatiotemporal context of everyday events, where autobiographical memories are anchored. From this point of view, it is plausible “that semantic memories arise from combinations of hippocampal event-unique memories but eventually they can become independent of the hippocampus” (Burgess et al, 2001). An alternative or perhaps a complementary theory suggests that the hippocampus might not just be about spatial memory but rather 'a memory space'. Eichenbaum and Cohen (2014) argue that “the hippocampus enables relational representations that bind in memory the elements of experiences and links memories via their common elements, composing a ‘memory space’”. The relational memory theory (Eichenbaum et al, 1999) suggests that spatial mapping is a specific form of relational memory and supports the view that mental maps “can be organized in space, time, and conceptual dimensions” (Eichenbaum & Cohen, 2014).

Eichenbaum and Cohen, claim that the hippocampal system is responsible for the “relational mapping of objects and actions within spatial contexts, representing routes as episodes defined by sequences of places traversed, and relating spatial episodes to existing semantic maps of space that can support navigation via novel

route construction” (ibid). Thus, the relational system supports spatial and non-spatial factors with the same underlying mechanism. This general mechanism involves the representation of events as items within a specific context and a sequence or flow of these events engenders the representation of episodes. The related events and episodes are linked to relational networks and support the emergence of flexible and novel inferences, drawn from memory across spatial and conceptual dimensions (Eichenbaum & Cohen, 2014). Herweg and Kahana (2018) discuss as well, how spatial memory can be involved in the association between different kind of features. They provide an illustrative example of a study where participants had to learn a conceptual 'map' (two-dimensional space) of visual bird features. Subsequently, they were asked to view and imagine how birds would look like along a certain path of features. During these imagined trajectories in the conceptual space, a grid-like activity coding was observed in several areas that have been also involved in navigation (Constantinescu et al. 2016 in Herweg and Kahana, 2018).

Building upon this framework, Buzsáki (2005) proposes an elegant idea that aims to explain the relationship between episodic learning and the emergence of 'maps', both spatial and conceptual. He argues that the transition from episodic to semantic memory is homologous to the transition from wayfinding based on path integration to map-based (allocentric) navigation. Route learning involves coding of a series of cues. It is like learning a linear, one-dimensional sequence of presented or visited items which involve episodic memory (Buzsaki, 2005; Buzsáki, 2006). In this kind of one-dimensional travel, place cells have been found to respond unidirectionally, since the firing of the same sequences of cells is strengthened in the forward direction. This has been observed for example in experiments using radial arm mazes, where neurons are typically unidirectional in the arms of the maze. However, this response changes at the centre of the radial maze after exploration from different directions and place cells then have a similar response as they do in open fields (Herweg & Kahana, 2018). Route explorations that have common junctions give rise to the omnidirectional response of place cells since the activated neurons are tied to different episodes.

Omnidirectional place cells therefore no longer depend on the temporal or self-reference context since they “become part of multiple neuronal trajectories” (Buzsáki, 2006) and form “time-independent associations” (Herweg & Kahana, 2018). They are considered the hallmark of the cognitive map along with the grid cells in the entorhinal cortex (Buzsaki, 2005). Omnidirectionality is an indication that the neuron has become part of a 'hub' in the network or part of an explicit assembly that “collectively define[s] or symbolize[s] the 'meaning' of an item” and “such explicit, higher-order representation is invariant to the conditions that created it” (Buzsáki, 2006). The emphasis here shifts from first-order relations to the explicit nature of the representation. Along the same lines, O'Keefe suggested as well that omnidirectional cells do not code simple sensory input but it is more likely that they compute the more abstract concept of place or location (O'Keefe et al, 1998).

Buzsáki's theory is based on the idea that semantic memories are formed gradually and evolve in steps from overlapping multiple episodes that have common items such as junctions. And these junctional items “can free the common item from its context(s)” and allow a graph-like knowledge of the environment to emerge (Buzsaki, 2005). While episodic memories are linked to theta oscillations in the hippocampus (that have a duration of several seconds), the semantic memory is thought to be associated with a non-theta sharp wave burst, a self-organizing pattern that lasts about 150ms, that compresses the information of many episodes. These sharp waves may be the means by which the brain transfers “solidified maps and semantic information from the hippocampus to the neocortex” (ibid). At the level of synchronous activity of a larger population of neurons which can be recorded by scalp electrodes, semantic memory performance has been associated with a decrease in alpha power (Buzsáki, 2006). Klimesch's argues that alpha oscillations are associated with controlled access to and retrieval from a 'knowledge-based system' and facilitate 'semantic orientation' during these processes (Klimesch, 2012).

One important point in Buszaki's theory that calls for further discussion is regarding the form of learning that is implied. Buszaki emphasizes that semantic memories evolve gradually and do not emerge suddenly. Semantic knowledge, he argues, requires the occurrence of multiple overlapping episodes with common junctions (Buzsaki, 2005). If we apply the same idea to a non-spatial conceptual dimension, as

the relational theory suggests, then the emergence of semantic knowledge will involve some sort of multiple overlapping encounters of a given item. However, such an explanation does not include the case of the spontaneous insightful one-shot learning and the sudden Aha! experience but only a form of gradual learning that emerges incrementally by repeated exploration. If, as the relational hypothesis suggests, the 'spatial memory' in the hippocampus is a rather a 'memory space' and includes other non-spatial relations or dimensions (i.e. conceptual) then there should be some way to explain the emergence of semantic knowledge also in the case of insightful learning.

One possible interpretation comes from Buszaki's comments on the prerequisite of visiting the same position from different directions, where he adds the following footnote: "...a map can be generated without vision, as well, in which case each place must be physically visited. With vision, it may be sufficient that the eye 'visits,' i.e., explores, every place" (Buzsáki, 2006). This perhaps suggests that omnidirectionality and semantic knowledge may also emerge through visual exploration and imagination (mental imagery). Having a mental representation of spatial relations that has been generated from a verbal description or from studying a physical map perhaps facilitates the transition to explicit and reportable knowledge through visual exploration. In these cases, a landmark-location (environmental shape) that is salient in the initial mental representation generated when studying a map, is 'visited' again during actual navigation but from a different frame of reference, through an egocentric viewpoint. Even though Buszaki's theory is quite elegant, it has not yet been verified experimentally (Herweg & Kahana, 2018) and the idea that his theory might include as well cases of insightful learning is merely a speculation.

Omnidirectionality also seems to be greatly influenced by the amount and distribution of the visual information of the environment. Herweg and Kahana (2018) discuss the emergence of omnidirectional firing during human navigation in virtual reality urban environments and highlight some interesting differences between two studies that used intracranial recordings. The experimental task was quite similar in both studies: participants had to play a video game pretending to be a taxi driver (Ekstrom et al, 2003) and delivery person (Miller et al, 2013). In Miller and colleagues' 'delivery person' study participants spent some time to familiarise with

the environment before the task, and thus they had more opportunities to create multiple overlapping episodes at common junctions. However, most of the hippocampal place cells (72%) were direction-dependent. Even though both city environments had defined routes and were not open environments, in the ‘taxi-driver’ study researchers reported predominantly omnidirectional coding. The main difference between the two cases is that Ekstrom and colleagues’ study had smaller buildings and wider roads which presumably allowed more extended ‘eye visits’. In contrast, in Miller and colleagues’ experiment, the environment contained constrained paths and high building. Unidirectional firing has been associated with maze-like environments and that leads to the assumption that in the second study it might have been more difficult for participants to orient. This assumption seems reasonable considering that the place cell’s omnidirectionality is dependent on an intact head direction cell’s input (Herweg & Kahana, 2018). The comparison of the findings from these two studies suggests that omnidirectional firings seem to depend at a great degree on the available visual information of the environment and not just the number of junction-crossings and re-current overlapping of episodes as the relational theory suggests.

One of the main differences between the relational theory and the cognitive map theory is the type of learning that is suggested to underly the formation of the representations in the hippocampus. The relational theory points towards traditional associative learning theories (Hassabis, 2009) while the cognitive map supports the idea of one-shot incidental learning (Burgess, 2008). Hassabis (2009) comments on the debate between these two theories, and he suggests a novel perspective regarding the function of the hippocampus. He suggests that apart from its mnemonic role it also has a non-mnemonic role, a dynamic integration function. This function is “key to the rich recollective experience that accompanies episodic memory recall” and facilitates the binding of the information into “a spatially coherent whole”. Episodic memory is a rich re-experience of a past event which involves the reconstruction and re-experience of the scene. A similar “scene construction” function seems to be involved in the imagination of new experiences (ibid.) This is supported by evidence from a lesion study where patients with hippocampal damage exhibited difficulties in “scene construction”, that is imagining coherent spatial scenes (Hassabis et al, 2007).



Hassabis (Hassabis, 2009) argues that in parallel with a gradual encoding during overlapping experiences, the hippocampus is involved as well in the rapid integration of information across experience during episodic memory recall. Evidence from a relevant recent study shows that the hippocampus not only supports the creation of separate memories for distinct episodes (e.g. AB and BC) but is also involved in tasks that require inferences across distinct episodes (e.g. AC) (Koster et al, 2018). The unseen connecting element (e.g. B) that support the inference across the separated experiences appears to be ‘reactivated’ during retrieval within the entorhinal cortex (ibid.). This suggests that the retrieved memory (e.g. the shared component) is presented as a new input to the hippocampus. The researchers argue that the hippocampal system acts as a “big-loop recurrent circuit whereby the output of the system is recirculated as a new input”. This allows the “recombination of related episodes at the point of retrieval” and the evaluation of commonalities and higher-order structures across separated experiences. Therefore, considering these recent findings the theory of “big-loop recurrence” appears to explain the rapid evaluation of the structure among experiences and the construction of higher-order representations during retrieval. This mechanism may function in parallel to the encoding-based processes that occur by recurrent overlapping episodes.

#### **2.2.4 Brain Dynamics of Spatial Navigation and Orientation**

Theta oscillations have been often reported during navigation in virtual reality environments. Increased theta activity over the frontal midline area has been associated with memory operations (Mitchell et al, 2008) for example encoding new spatial information when “new hallways come into view” (Bischof & Boulanger, 2003), processing of spatial cues (Kober & Neuper, 2011) and during memory retrieval “of previously traversed segments” (Plank et al, 2010). Increased theta power in frontal regions was also observed “during more demanding navigation periods” (Kahana et al, 1999). In addition, a theta effect reliably distinguished between landmarks of interest (targets) versus non-targets or neutral landmarks (Weidemann et al, 2009). Theta oscillations during navigation have been associated with sensorimotor processes (Ekstrom et al, 2005) but with spatial updating and encoding of translational movement as well (Bush et al, 2017; Herweg & Kahana, 2018; Kaplan et al, 2012). Also, according to the literature, theta oscillations

typically occur at a lower frequency during virtual navigation peaking around 3.3Hz (Bohbot et al, 2017; Jacobs, 2014). Delta/theta power increases (in the human hippocampus) were observed for longer versus shorter distances (Bush et al, 2017; Vass et al, 2016)

Furthermore, the literature suggests that brain activity is greater at the right hemisphere during human spatial navigation and knowledge of spatial locations (Jacobs et al, 2010). Studies on temporal and parietal lesions, support these findings and suggest that right hemisphere is involved in remembering locations and perceiving spatial relations while left regions contribute to remembering temporal order of events and in facilitating visual constructive tasks (Dudchenko, 2010; Spiers et al, 2001). Analogous differences between right and left hemisphere have been also reported in the P3 literature. The P3 amplitude is larger over the right compare to the left frontal/central areas in an oddball task. Which, according to Polish, is reasonable “given a frontal-parietal right hemisphere attentional network system” (Polich, 2007).

In a virtual reality taxi-driver game, patients with depth electrodes at the hippocampus, parahippocampal gyrus and several other areas (e.g. temporal, parietal, frontal) exhibited increase theta oscillations during movement vs. stationary periods. Because the theta effect was present not only in the hippocampus but as well in the neocortex, the researchers suggested that theta oscillations during navigation might be linked to attention and sensorimotor integration (Ekstrom et al, 2005). However, another study (Bush et al, 2017) where patients were asked to find the location of previously presented object in an open virtual reality environment (i.e. arena) also reports increases in movement-related hippocampal theta (for both low, 2-5Hz and high, 6-9Hz theta) that were observed during movement and at the initiation of movement compared to stationary periods. The theta activity was also greater for longer paths which according to the authors, shows a direct implication of human hippocampal theta “in the encoding of translational movement”. Another interesting finding from this study is that increases in theta power during movement onset did not show any significant difference between encoding and retrieval cases (ibid.).

Using a similar experimental paradigm, Kaplan and colleagues (2012) examined the relation of theta band activity to self-directed learning and self-initiated movement using non-invasive magnetoencephalography (MEG), and the associated brain regions using fMRI. During movement initiation, there was a strong theta increase associated with the hippocampus and the midline frontal region (medial prefrontal cortex) compared to stationary periods. They also found interesting relations between theta power and cognitive performance. Theta power increases during navigation and stronger theta increases during movement initiation vs. stationary periods were associated with better memory performance. Performance-related increases in theta power during movement may reflect memory encoding, as the authors suggest (ibid.).

Javadi and colleagues designed a virtual environment to test participants' neural and oscillatory responses to changes (modulated by 'lava flows') in the available paths to a goal location in a previously learned virtual environment (Javadi et al, 2018). During wayfinding, a sudden availability of true shortcut, as opposed to a false shortcut that increases the path length to the goal, elicits an increase in frontocentral theta activity (Javadi et al, 2018). Furthermore, a backtracking behaviour that correctly changes the direction of movement to the goal by decreasing the path length (a behaviour which is highly related to the experience of re-orientation) is accompanied by posterior alpha power decrease (ibid). The authors interpreted the alpha decrease of the backtracking event as a change in the allocation of attentional resources. The frontocentral theta response was thought to reflect either retrieval and imagery or alternatively an increase in conflict between choices or stimuli which according to the researches might be more consistent (ibid.). These findings share similarities with the observations in experiments on the Aha! moment. Detecting and monitoring cognitive conflict was associated with activity in the ACC during insightful problem solving (Mai et al, 2004; Qiu et al, 2006). Support for this possible association comes again from research on navigation where researchers reported an increase in theta reflecting increase task demands during critical points of the navigation task and that this response was generated in the ACC (Lin et al, 2015).

Evidence of EEG dynamics, closely relevant to spatial orientation, comes from a line of research that separates participants into two groups based on their responses on a

task that shows whether they rely on an egocentric frame of reference (turners) or an allocentric (non-turners). Gramann and colleagues (2010) examined the EEG dynamics of the two groups during turns in a virtual tunnel passage (and used ICA for source localization). Stronger alpha decrease in alpha power at or near the retrosplenial cortex (as well as near the visual cortex and parietal cortex) was observed for non-turners when approaching and during tunnel turns. This was interpreted by the researchers as “a continuous translation of egocentrically experienced visual flow into an allocentric model of their virtual position and movement” (ibid.). These findings were replicated by a second study that used the same experimental paradigm (Chiu et al, 2012). Researchers investigated the EEG dynamics during the turn in the virtual tunnel (encoding phase) and the retrieval phase of pointing to the origin of the path. Alpha decrease was observed for both groups during encoding as well as during retrieval, in or near retrosplenial and at parietal and occipital cortices. However, alpha power decrease was stronger for non-turners at these areas and was related to the retrieval of allocentric information from the retrosplenial cortex, and visual imagery in occipital areas based on the retrieved information. Increase theta activity was also observed during the homing decision of the response (Chiu et al, 2012).

In a more recent study on spatial orientation, researchers compared the EEG dynamics between the two subject groups in a virtual environment structured with allothetic information (Lin et al, 2015). The brain dynamics during orientation (passive movement) were compared with a control condition (reproducing the pointing direction of an arrow encounter at the beginning of the trial). The ICA source localisation revealed a cluster of increased theta activity in or near the anterior cingulate cortex reflecting working memory demands (stronger for turners). During straight segments, both groups exhibited a decrease in alpha power in the retrosplenial complex. Alpha desynchronization in the parietal region before the turn was associated, for both groups, with increased spatial attention and the integration of information from the visual flow with a representation of self-location. Alpha desynchronization (8-13 Hz) in or near retrosplenial cortex, was stronger for non-turners and allocentric navigation was associated with a performance-related alpha decrease in the same region. Alpha decrease, generated at retrosplenial cortex was again interpreted as reflecting the integration of visual-flow

information from occipital and parietal regions with allothetic cues “to map egocentric viewpoints onto an allocentric reference frame” (Lin et al, 2015).

Theta (low and high frequency) increases at frontal (and parietal) regions and alpha decrease at posterior regions of the brain in navigation and orientation studies, seem to be related with increased task and memory demands (encoding and retrieval processes) and the translation between reference frames respectively. The paragraphs that follow provide a brief review from studies that are not specifically focused on navigation but might be relevant to the processes of re-orientation such as recognition and episodic and semantic memory.

Increase in theta might be related to monitoring new information since it is associated with increased working memory demands “reflecting sustained attention to the processing of new information” (Klimesch, 2012). Central theta has been reported to increase with decision difficulty in a recognition memory task and was related with increased reaction times (Jacobs et al, 2006). It is reasonable to assume the implication of the anterior cingulate cortex during these processes, which is near central electrodes since it has been often reported in decision making, conflict resolution, and attention monitoring. Significant theta band synchronization in or near ACC was observed 'during critical phases of the navigation task ', reflecting spatial working memory demands (Lin et al, 2015).

Evidence for theta effects in episodic memory studies is not as robust compared to finding from studies on memory performance during navigation, according to Herweg and Kahana (2018). They comment that a large number of studies have reported increased theta power during episodic memory but several others have reported a decrease. However, findings for theta increases during episodic memory retrieval are more consistent and increased theta power has been observed before the spontaneous free recall and distinguishes successful recollection of contextual information (ibid.).

An interesting line of research, which might also be related to the theory developed by Buzsáki, 2005 (section 2.2.3), investigates the relationship between episodic and semantic memory to theta and alpha band oscillations. Earlier work by Klimesch and

colleagues (1994) examines the brain dynamics of participants during an episodic and semantic memory task. Pairs of words were presented to the participants in both the semantic and episodic task. In the first case, participants had to decide whether the words were semantically congruent and in the second whether the pair was previously encountered in the semantic task. Results showed that the magnitude of the alpha decrease was greater for the semantic task and theta increase was observed only for the episodic task. Interestingly, in this study, Klimesch discusses the possible significance of the P300 for episodic memory (in line with Donchin's context updating) as well as the possible relation between encoding episodic information and hippocampal theta activity (Klimesch et al, 1994). In a subsequent review by Klimesch (1999), a series of studies on semantic and episodic tasks are examined in relation to alpha and theta modulations. Although it is difficult to separate the neural rhythms that contribute to each task since tasks that involve episodic memories may also include items that have a semantic aspect, Klimesch claims that increases in theta are related to the encoding of new information and that alpha is related to search and retrieval processes in semantic long-term memory (Klimesch, 1999).

Alpha power decrease at parietooccipital areas is an indication of increased cortical activity and could be related to the processing of sensory-semantic information (Klimesch, 2012; Klimesch et al, 2007). Klimesch (2012) argues that alpha event-related desynchronization during retrieval varies according to the “semantic content of the information that is retrieved”. The literature, therefore, suggests that there is most likely a link between alpha power decrease and semantic memory and the controlled “access to information that represents knowledge of the environment “ (Klimesch, 2012). On the other hand, delta/theta increase has been related to episodic memory, encoding and/or retrieval, decision making and spatial working memory load.

### 2.3 Spatial Configuration and the Embodied Mind

Several cognitive processes are involved in successful wayfinding. Spatial updating, as we have seen in the previous section of this chapter, involves processes that allow the automatic computing of one's spatial relation with the immediate environment and it involves the use of landmark, route and survey knowledge and scene recognition (Riecke et al, 2002). An automatic '*back up mechanism*' related to spatial updating is path integration. Path integration involves the integration of information from kinaesthetic and vestibular cues and computes the current position and orientation in relation to a location of origin (Riecke, 2012). Additionally, the cognitive process of self-localization and orientation provides the 'you are here' sign of the mind, which is a "'gut' feeling of being in a specific spatial context, and intuitively and spontaneously knowing where one is with respect to the immediate surround" (Riecke & von der Heyde, 2002).

In order to move towards a certain goal, the navigator needs to use information that is stored in mental representation to estimate the path to the goal and plan further movement. Mental spatial representations, are the way the mind stores and recalls spatial information from memory. These representations are influenced by the initial perceptual processing and encoding of the environmental information during learning. As several experiments show, these processes result in systematic distortions and simplifications of the spatial representations. This shows that the 'cognitive map', which facilitates spatial updating and 'knowing where one is' during navigation, is not an exact copy of the external world but follows laws that structure hierarchically our spatial knowledge. 'Knowing where one is' is a crucial element for successful wayfinding and the related spontaneous 'gut' feeling of spatial presence depends on the immediate spatial context and its distinct characteristics in terms of the environmental geometry, spatial configuration, landmarks and other visual and non-geometric environmental variables.

However, the specific moment of re-orientation depends on the use of geometric information of the surrounding space rather than non-geometric features. Even though non-geometric cues may have an impact over behaviour after disorientation, it remains debated "whether this use of non-geometric features reflects incorporation

of non-geometric information into reorientation or the operation of a separate post-reorientation mechanism that checks the features at the target location for consistency with visual memory” (Julian et al, 2018). A recent study on disoriented mice, for example, shows that the recovered hippocampal map was aligned according to the shape of the chamber (e.g. rectangular, square, isosceles triangle). However, visual cues had no effect. This supports the idea that the boundary geometry plays a significant role in the recognition of spatial locations (Keinath, et al., 2017 in Julian et al., 2018).

Although geometric cues and spatial configuration play a central role in re-orientation and navigation within the built environment, only a small number of behavioural neuroscience studies bring the spatial factor at the same level of importance as they do with the psychological and cognitive theories. Environmental modelling techniques used in the space syntax literature offer a valuable tool that quantifies the visuospatial properties; and thus, allows to incorporate a quantitative context-based analysis in empirical studies that seek to understand the relevant behavioural and neural responses.

This section of the literature review chapter discusses these issues and reviews some relevant findings that relate space syntax research and isovist properties to spatial behaviour and cognition. The last part is focused on the main psychological factors that affect exploratory behaviour, as suggested by the literature of environmental psychology. The relevant theories point towards two main predictors of preference for spatial scenes, spaciousness, and complexity, which can be best described by the isovist measures of area/revelation and clustering coefficient /visual control, respectively. These two factors form the basis of the two hypotheses that the thesis tests in order to examine where it is more likely for the Aha! moment of spatial re-orientation to occur.

### **2.3.1 Perceptual Simplification of Spatial Layouts**

Evidence from several experimental tasks on spatial cognition illustrate the consistent distortions or simplifications of our mental spatial representations, which are based on properties of the environmental stimuli. Spatial chunking or clustering into small meaningful representations “allows us to activate only the spatial



information that is needed in a given moment enabling us to operate within the capacity limits of working memory” (Avraamides et al, 2012). It seems to occur where there are salient discontinuities or discrete changes (Klippel et al, 2012). Spatial chunking is also evident when mental spatial representations are externalised (Richter & Klippel, 2005). When giving verbal descriptions, we usually combine several similar actions into a single route direction. In this way, the phrase '*along the river*', constitutes an intrinsic reference frame and allows the compression of several decision points. Or for example, grouping effects that occur during inspection seem to be present when visual mental images are externalised into diagrams (Engel & Bertel, 2005).

The organisation of spatial knowledge seems to rely on several heuristics that aim to reduce the information load. Two basic heuristics that are identified by Tversky (1981) and seem to distort the representation of spatial information of environments and maps are the alignment and rotation heuristics. These mechanisms of simplification, derived from principles of perceptual organisation, are evident in systematic errors during recall. Figures that are perceived as grouped together, they are remembered as being more aligned than they are (alignment heuristic) and orientation of figures is remembered and anchored in relation to a certain frame of reference (rotation heuristics) (Tversky, 1981).

The alignment and rotation heuristics suggest that mental simplification mechanisms seem to follow laws and principles that are also present in visual perception. Another example of such simplifications is the 'route effect' (McNamara 1984 in Klippel et al. 2005), which describes the tendency of judging cities connected by a road as closer. It has been traditionally considered as a result of the knowledge we have of the functionality of this route connection. Klippel and colleagues suggest that this effect may “be a by-product of perceptual organisation” rather than an organisational principle in memory (Klippel et al, 2005). Perceptual processes actively organize the spatial information into part-whole relations, following Gestalt principles of perceptual organization (Tversky, 1981; Tversky & Schiano, 1989). According to the Gestalists' view, the information of a stimulus is grouped together following principles of similarity, proximity, symmetry, and closure forming part-whole

relations. And judgments on spatial relations seem to be influenced by manipulations of these Gestalt principles (Klippel et al, 2005).

Klippel and colleagues suggest that wayfinding may be associated with the structure of the environment, that is the physically present features but also with the function which is the relation between the structural elements and action (Richter & Klippel, 2005). The simplifications of the spatial representation are also often influenced by functional clusters, that is places and objects associated with the same action or by other subjective factors (e.g. idiosyncratic preferences). For example, perceptual salience of a path (based on attractiveness of objects within the path) may have a stronger effect on wayfinding behaviour (selection of path) than a path that has long lines of sight or that suggests further multiple path choices, which are considered two main strategies during wayfinding (Frankenstein et al, 2010). On the other hand, distance estimation can be influenced by the nature of affectiveness of the goal (positive or negative affect) and as a function of the degree of urgency (Johnson et al, 2010). The way we shape and distort our cognitive representations is greatly influenced by how we perceive environmental stimuli.

These distortions seem to occur at the level of perception but as well as during encoding and retrieving information from memory. To study the factors that influence the selection of intrinsic reference frames in spatial memory, researchers usually use alignment experiments which tend to show that spatial representations are orientation-dependent and are more easily accessible from the preferred viewpoints. Alignment effects observed in behavioural studies, suggest that pointing performance based on memory of objects is higher when view is aligned with is salient axis of the environment or other intrinsic frames of reference as well as when the viewpoint is aligned with egocentric heading during exploration (Herweg & Kahana, 2018; Julian et al, 2018). Mental representations of spatial layouts might be aligned with specific route directions or environmental cues e.g. a representation might be oriented in relation to (directional) landmarks (Basten et al, 2012). Intrinsic frames of reference, for a set of objects might be selected on the basis of various cues, such as “participants’ viewing perspective and other experiences (e.g., instructions), properties of the layout (e.g., the objects may be grouped together on the basis of similarity or proximity), and the structure of the environment (e.g.,

geographical slant)” (Mou, 2007). These frames of references are used as the basis for organising the knowledge that we acquire of the spatial structure, the layout geometry of the environment.

Spatial representations are therefore organised on the basis of available spatial cues during encoding. Research suggests that spatial relations that are encoded during different phases result in distinct spatial representations, which are organised by different frames of reference (Avraamides et al, 2012). Avraamides and colleagues investigated the integration of spatial information from distinct perceptual experiences. They tested participants performance in a judgment of relative direction task, for distinct spatial arrays with bilateral symmetry axes that were misaligned with participants’ initial viewpoint (during learning). Judgments regarding the spatial relation of objects within the same array reflected that the spatial representation was anchored to the axis of symmetry while judgments between the arrays were facilitated by the participant’s view during learning. The researchers concluded that the integration of information, from within and in-between layouts, follows hierarchical structures “organized around distinct microreference frames whose relation is specified by a more global macroreference frame” (ibid.). This sort of hierarchical structure must be also present in a large-scale urban environment since large-scale layouts are not experienced simultaneous but with “an extended temporal separation” (ibid.)

Theories from the field of the built environment share similar views and suggest these sort of distortion are “instances of what we might call the Kantian simplification: people impose more geometry on the situation than it actually has” (Hillier, 2006) and that “our notions of distance are compromised by the visual, geometrical and topological properties of [spatial]networks” (Hillier & Iida, 2005). The underlying intuitions of our geometric decisions is a subject that intrigues the interests of Bill Hillier (Hillier, 2006). He suggests, in a quite parallel line with the Gestaltist's views, that people seem to synchronise distinct objects into an overall higher *template*. “People”, he claims, “seem to have some kind of non-local internal representation by which they synchronize discrete experiences into a non-local picture. There is some kind of embedded rule an abstract scheme of spatial relations” (ibid.). In addition, he claims that the way we encode spatial information is probably

based on topological simplifications and that this may be related to the shift from route-based knowledge to map-based, that is from egocentric to allocentric understanding (ibid.). Consequently, current views from both the cognitive sciences and the built environment support the idea that the cognitive map is rather hierarchically organised, fragmented and allows for graph-like knowledge of spatial relations (Herweg & Kahana, 2018; Julian et al, 2018).

### **Environmental legibility**

Montello (2005) addresses the differences between navigation in the built and natural environments. The visual complexity of natural scenes -irregular asymmetric and curved shapes- creates a certain degree of visual homogeneity. While on the other hand, the built environment has rather a 'more minimalistic' character. The structure of the built environment involves more regular patterns with right angles and straight lines, and while certain spatial layouts may have great differentiation in terms of height, colour or scale, others may lack variation to an extreme degree (ibid.). The ease or difficulties we may experience while navigating in physical environments (both in natural and built environments) depend on the visual and structural characteristics of these environments (Montello, 2005).

An interesting analysis of the characteristics that affect orientation and wayfinding in physical environments is offered by Wiseman (1981). He comments that the 'legibility' of an environment, that is "the extent to which it facilitates the process of wayfinding", is closely related to "the ability to see through or out of a setting, the extent to which one location looks 'different' from others and the overall plan or layout of a setting". Montello (2005) discusses further these environmental variables of differentiation, visual access and layout complexity that seem to influence participants' wayfinding behaviour. Differentiation in terms of size, shape, colour, texture, etc. acts as a wayfinding aid because "the differentiated parts are more distinct and memorable". However, if differentiation occurs at an extreme degree it might lead to disorientation. Visual access is defined as "the degree to which different parts of an environment can be seen from various viewpoints" (ibid.). Locations with a greater degree of visual access, then, provide significant cues for orientation. Montello discusses here the contribution of isovist theory (and isovist

characteristics of size and shape) for the systematic analysis of visual access. The third factor of layout complexity is more difficult to describe since it entails part-whole relations. Although, for example, differences in smaller districts of a certain spatial layout may increase the degree of complexity of the layout what is more critical is the way that these different parts are organised. He suggests that “the overall shape or ‘gestalt’ of a path layout can determine whether a particular element is disorienting” and provides the example of how a curved street belonging to a radial pattern might not be a disorienting element if the pattern is legible. Thus, layouts that have ‘a good form’ facilitate orientation (Montello, 2005).

The concept of ‘legibility’ and ‘imageability’ are issues that have been discussed much earlier by Lynch (Lynch, 1960), along with the part-whole relations. Lynch comments:

In such a whole, paths would expose and prepare the districts and link together the various nodes. The nodes would joint and mark off the paths, while the edges would bound off the districts, and the landmarks would indicate their cores. It is the total orchestration of these units which would knit together a dense and vivid image... (ibid.).

Paths, edges, district, nodes, and landmarks are “empirical categories within and around which” the mental image of the whole is organised. Even though Lynch's empirical categories are entirely based on externalised diagrams of mental maps that participants drew, his theory is considered a great contribution in understanding the relation of the spatial configuration and the mental representation. A ‘legible city is “one whose districts or landmarks or pathways are easily identifiable and are easily grouped into an over-all pattern” (ibid., p.3). It has a direct relation to the ‘imageability’ of the environment which is “that quality in a physical object which gives it a high probability of evoking a strong image in any given observer” (ibid.). However, one of the limitations of this theory, as he also mentions, is the “lack of information on element interrelations, patterns, sequences and wholes”. This rather suggests that necessity for introducing new methods into this area of study, such as a quantitative structural/topological analysis (Conroy Dalton & Bafna, 2003), to fully

understand from other perspectives and other disciplines as well, the notion of 'imageability'.

Two interesting studies attempt to describe a possible 'syntactical' and 'digital' image of the city and offer a quantifiable basis for Lynch's elements. The first study by Conroy Dalton and Bafna (2003) examines the relation between these elements and space syntax's spatial descriptors while the second by Montello and Ratti (2009) focuses only from the perspective of visibility in terms of 2D and 3D isovist fields (the vertical dimension is also considered here in the authors' proposal of 3D isovist measures). The studies suggest that paths are analogous to the axial-line –where significant paths are the highly integrated ones- and can be characterised in terms of their 'visual rhythm', expressed as histograms of isovist properties along the path (path isovist) <sup>11</sup>. Nodes, are considered as open spaces (e.g. squares, parks) into which an observer can enter (Morello & Ratti, 2009) or on the basis of their contribution to a sense of orientation <sup>12</sup>, and can be described in terms of isovist properties of concavity, the area to perimeter ratio, mean isovist length, circularity and entropy and based on their proximity to highly integrated axial lines and strong visual asymmetry (Conroy Dalton & Bafna, 2003). Districts are more difficult to be 'captured' using such techniques, although it should be characterised by local intelligibility (Conroy Dalton & Bafna, 2003) and could be described in terms of its boundaries (paths and edges) (Morello & Ratti, 2009). Edges, as linear elements, are visually prominent and continuous in form, can be approached in terms of the distribution of isovist radials lengths and its regular increase or decrease. And, finally, landmarks can be characterised by 'idiosyncratic isovist shapes', can be "accessed from spatially integrated lines of movement" (Conroy Dalton & Bafna, 2003) <sup>13</sup> and are visually connected with strategic points in the city in order to 'provide a constant reference' (Morello & Ratti, 2009). Dalton and Bafna (2003) comment that "mental map is essentially structured by the spatial elements [nodes,

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<sup>11</sup> Some paths, for example, may have a regular and controlled rhythm while in others may have certain patterns of "*crescendo effect due to the increasing visual openness*"

<sup>12</sup> Conroy and Bafna (2003) refer to the Piazza San Marco, which is characterized by Lynch as an example of a node, to highlight the contribution of nodes in orientation: "*a visitor may not only be oriented locally within the piazza but also use that orientation to place himself with respect to the rest of the city*"

<sup>13</sup> The authors here base their analysis on Peponis's study on landmarks in Corfu in 1998

paths, and districts], which may then be elaborated, or fine-tuned by the addition of visual elements [edges and landmarks]”. Their study argues for the interdependency of Lynch’s ‘imageability’, which focuses on visually distinctive elements, with Hillier’s notion of ‘intelligibility’ which is more related to the spatial structure. They conclude that the structure permits the recognition of these elements which implies the inherently cognitive basis of space syntax.

‘Intelligibility’ is a popular theme in the space syntax literature which suggest strong links with spatial cognition (Conroy Dalton et al, 2011; Penn, 2003). The concept of intelligibility (Hillier, 1998) is fundamentally related to our ability to make inferences at a strategic location about the global spatial structure that lies beyond our immediate visual local cues. Our ability to find our way in complex environments depends at some degree on the relation between local visual cues and the global spatial structures. In an intelligible environment, as opposed to maze-like environments, a well-connected immediate visual field can be a strategic space for wayfinding since it can provide cues about the spatial structure that lies beyond (Conroy Dalton et al, 2011).

### **2.3.2 Environmental Modelling and Spatial Cognition**

Neurophysiological and behavioural experiments on spatial cognition are often only focused on the relevant cognitive and psychological theories and are designed with the objective to yield successful neural and behavioural measurements. However, a growing number of researches argues for the need of using these methods in more ecologically valid experiments that simulate better the dynamic and complex context of actual everyday human experience (Dara-Abrams et al, 2010). A central issue that should be taken into consideration for the design of such ecological experiments, is, of course, environmental properties. Investigating the cognitive phenomena and experiential events in relation to the properties of the environment is a proposition that finds strong support in the theories of enaction, the structural coupling of the embodied mind and environment. However, examples of studies on spatial cognition and related brain dynamics that employ adequate “rigorous techniques for characterizing environments and their perceptually and cognitively relevant properties” are rather rare (Dara-Abrams et al, 2010). The design of such experiments requires a quantitative environmental modelling technique. Accurate

measurements of spatial variables offer the possibility to examine different space-driven experimental conditions. A context-based analysis permits the investigation of correlations between spatial properties and neural/behavioural measures. Space syntax, isovists, and visibility graph analysis are quite promising quantitative environmental modelling techniques, which can be combined with behavioural and neural measurements (ibid.)

Space syntax theory (Hillier & Hanson, 1984) was initially developed with the aim to capture the two-way relationship between spatial configuration and society (Conroy Dalton et al, 2012). It was originally used to represent and quantify spatial patterns and thus compare different urban spaces or buildings (Penn & Turner, 2002) and the associated social and cultural aspects. The principle idea that guides these analyses is the concept of permeability which, in simple words, refers to the degree of accessibility of each space (Dalton, 2011). The analytical tools used, within the space syntax community, to quantify aspects of the spatial configuration are based on different ways of spatial decomposition. One common space syntax technique is axial map analysis which involves the analysis of a connected graph of axial lines. Axial lines are the longest lines of sight within an environment (Hillier & Hanson, 1984). They are often used to investigate large scale environments such as urban systems. Convex space analysis, on the other hand, is usually used to investigate the spatial configuration at the building level. This technique is used to decompose spaces based on the mutual co-visibility within an occupiable void (e.g. room) and examines their interconnections (Dalton, 2011).

Another innovative technique is the visibility graph analysis (Turner et al, 2001), which is related to the notion of intervisibility. It is based on the description of space as a field of points that are organised in a grid. It connects “mutually visible points in a graph data structure” and can be seen as a combination of isovist analysis (Benedikt, 1979), which is the region of space visible from a given point, and axial graphs. Isovist ideally refers to the volume of space visible from a given point in space but it is often studied in two dimensions, as a horizontal section of the three-dimensional isovist. The resulting two-dimensional polygon surface can be analysed in terms of its area, perimeter, area to perimeter ratio, the distribution of radial lengths and several other measurements. The isovist method provides a quantitative



technique to formally describe and compare different locations in terms of the amount and the distribution of visual information. Inferences regarding different spatial configurations can be drawn in terms of the distribution of visual information from a single point and/or in terms of inter-visibility (isovist intersections) between different vantage points which are organised in a regular grid. This isovist-grid is the basis of the visibility graph analysis (Turner et al, 2001). It relies on the idea that “if the centre of one isovist lies within the isovist of another, then it is possible to move from one point in space to another”, which offers the possibility to create a graph of the interconnection of isovist spaces (Dalton, 2011).

Although space syntax techniques were not initially developed to examine the relation of spatial configuration to patterns of movement, a strong correlation has been revealed between the spatial structure and pedestrian flows as well as the co-presence of people in space. Penn and Turner comment that relevant findings suggest that “between 50 and 80% of the variance in pedestrian flows from location to location in an environment can be explained in terms of variations in configurational properties of those locations in the network” (Penn & Turner, 2002). These findings suggest that space syntax environmental modelling techniques can predict, quite accurate, aggregate pedestrian movement. However, the current challenge is to evaluate whether the model can also capture differences at the level of the individual such as individual decisions, behaviour and relevant cognitive processes.

An early attempt that explores the relationship between quantitative descriptions of the environmental shape and how individuals experience the transitions of visuospatial information can be found in Peponis and colleagues' work on convex partitions (Peponis et al, 1997). They propose the concepts of e-spaces and s-spaces, and by extension e- and s-partitions, to examined discrete changes in the environmental information that are encounter through movement in space (ibid.). Their objective was to identify these discrete changes or transitions between informationally stable units that are encounter through movement. They proposed a method of partitioning space which is based “on the thresholds at which edges, corners, and surfaces appear into the field of vision of a moving subject, or disappear outside it” (ibid.). The s-partition describes the threshold situation when a surface appears or disappears from the visual field of the observer. Transitions between s-

spaces are associated with changes in the available information about the shape. However, information within the s-space is not stable (information about shape changes). On the contrary, the ‘end-point partition’ identifies informationally-stable units (e-spaces) and crossing an e-line while navigating the environment results in a significant change in the available information. Nevertheless, one limitation of this technique, according to Dalton (2011) is that it “does not make it easy to quantify to what extent new information is encountered; it only makes it possible to measure to what extent or density a building or environment might create new information”.

Within the space syntax literature, apart from ‘intelligibility’ mentioned in the previous section, another area of research that seems to be related to spatial behaviour (and perhaps cognition as well), is ‘angularity’. It is based on observations of wayfinding behaviour of individuals in virtual reality environments that reveal that individuals tend to choose more ‘linear’ routes (Conroy Dalton, 2003). It describes the change of direction (angle) when passing from one space to another which is “represented as a set of 'weights' applied to the underlying graph representation that underpins all space syntax measures” (Conroy Dalton et al, 2011).

Apart from the tendency to minimise the angular difference between the actual heading and the ‘ideal’ heading towards their goal, individuals also tend to follow the longest line of sight when navigating towards a certain destination (Conroy, 2001). In addition, relevant findings suggest that the locations where participants choose to stop and make a decision for future direction are not random, but they correlate with large isovist area and long lines of sight. They are highly integrated and far from occluding surfaces (building edges) (ibid.).

Additional findings on wayfinding show that, after repeated exploration within complex buildings, movement patterns tend to correlate more with global measures such as ‘integration’, while initial exploration patterns are more related with local topological properties (Haq & Zimring, 2003). This indicates that when people acquire more spatial knowledge of a certain environment (increased familiarity) they tend to rely more on global properties of the environment during wayfinding. Another similar experiment on wayfinding in complex building investigates the relation between the degree of spatial knowledge and path choices. In this case,

people that are less familiar with the environment appear to use routes that have higher values of connectivity and integration (Hölscher et al, 2012). In addition, researchers have investigated the impact of familiarity and ‘environmental legibility’<sup>14</sup> on wayfinding performance (Li & Klippel, 2016). They reported that ‘environmental legibility’ has a major impact on wayfinding performance and spatial awareness while the acquisition of spatial knowledge was mainly affected by familiarity (ibid.).

Empirical studies focusing on the relation between space syntax variables and spatial behaviour have also used methods that include map sketching, pointing tasks, think-aloud protocols or tracking of individuals. Representative findings show, for example, that the representation of spatial knowledge of familiar environments (neighbourhood) as expressed through the sketch of maps, is sensitive to the axial-map integration value of space syntax analysis (Kim & Penn, 2004). That is, the maps that participants sketched showed that this external representation of their spatial knowledge reflected the same properties of the environment (integration values of the neighbour’s streets) as the space syntax technique (Kim & Penn, 2004). Additionally, evidence from a pointing task, which was used to assess spatial judgement and memory of the relation between campus buildings, show that participants’ performance can be predicted by the local integration values that are associated with the place in which they were asked to imagine themselves as situated while pointing to other locations (Dara-Abrams, 2006). A later real-world study focusing on isovist properties that may predict human spatial knowledge reported that participants were more accurate in the point task when standing at locations with high entropy and global integration values (Dara-Abrams, 2008). That means that representations of spatial relations are more accurately anchored to locations that have these properties and that higher entropy results in more accurate memory for locations (Dara-Abrams, 2008).

According to Montello, the topological and geometrical aspect formally described through space syntax, may be “potentially relevant to a variety of psychological

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<sup>14</sup> a concept integrating spatial syntax methods and Weisman’s (1981) wayfinding factors of visual access, differentiation and layout complexity.

responses” (Montello, 2007). He comments that space syntax has potentials to be an important contribution to a comprehensive theory of environmental psychology. However, he continues, space syntax research should also focus on several psychologically related spatial factors that have not yet been addressed such as environmental differentiation, the ‘gestalt’ overall shape of the environment, and individual differences in people’s response to layouts. He also suggests that space syntax “underplays the significance of metric spatial properties (including distance and direction)” (ibid.).

However, an earlier paper by Hillier and Iida (2005) addresses this issue of metric properties and discusses whether the correlations found between aggregate flows and space syntax measures have a cognitive basis. The authors examined the correlations between real movements (in four areas of London) and different concepts of distance in configurational analysis and concluded that “although it is perfectly plausible that people try to minimise distance, their concept of distance is, it seems, shaped more by the geometric and topological properties of the network more than by an ability to calculate metric distances” (ibid.). Through their thorough discussion and analysis, they argue that the correlations found between space syntax variables and aggregate flows are due to cognitive factors rather than network effects.

A recent study, using brain imaging techniques, provides evidence that supports the association between activity at specific brain regions and topological properties of the environment, as captured by space syntax’s graph-theoretic measures (Javadi et al, 2017). The researchers examined participants’ brain activity using fMRI while they navigated a film simulation of a recently learned urban area in London. During the goal-directed navigation, participants had to indicate at certain Street Entry points the optimal (shortest path) direction to the goal. Brain activity during these events was contrasted with a control condition and analysed in relation to graph-based measures and other environmental variables (e.g. step depth to boundary, line of sight).

Their results show that the right posterior hippocampus responds to local spatial properties and “tracks changes in the number of available path options”, as captured

by the ‘degree centrality’<sup>15</sup> measure. On the other hand, the right anterior hippocampus seems to respond to global properties and represents information about the “important streets in the environment”, in relation to step depth to boundary, line of sight and how central a certain location is within the network relative to all streets of the system, as captured by changes in the graph measure of ‘closeness centrality’<sup>16</sup>. The researches comment that these results are “consistent with the proposal that the posterior region codes fine-grain detail and the anterior codes global information” (ibid.). The activity in the posterior hippocampus might be related “to optimal retrieval of information for planning” while the anterior hippocampus might be involved in integrating information “during learning about the transition structure across the street network to aid optimal navigation” (Javadi et al, 2017).

Additionally, humans seem to acquire knowledge of global properties of the spatial layout after a certain degree of familiarity with the environment, since results from this study showed that only trained participants, as opposed to untrained, exhibited a hippocampal response to global properties during retrieval of topological information from long-term memory. They comment that it is likely that global processing of network topology in the hippocampus will correlate positively with prolonged exposure to the environment (Javadi et al, 2017).

The name ‘space syntax’ indicates a metaphor from the field of linguistics and the idea that a series of words within a sentence are combined into a meaningful outcome. Conroy-Dalton and Hölscher comment on this linguistic analogy and highlight that:

Configurations of spaces have not only a grammar but also a ‘syntax’: the pattern of relationships between spaces. It is this pattern of spatial relations that permit configurations to be meaningful and it is hypothesized that

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<sup>15</sup> Degree centrality is defined as “the number of connecting street segments to any street segment” (ibid.).

<sup>16</sup> Closeness centrality is defined as “the reciprocal of the sum of the topological distance from that segment to all other segments. It reflects how likely it is that a segment is an origin or destination segment”. (ibid.)

people have an innate ability to ‘read’ or comprehend these meanings.  
(Conroy Dalton et al, 2012).

Consequently, the term ‘space syntax’ suggests that this theory and method of analysis is concerned with how patterns of spatial relations become meaningful and “how the meaning of spatial environments is communicated” (ibid.). These questions reveal the strong connection of this environmental modelling technique to other related academic fields such as environmental psychology and spatial cognition.

### **2.3.3 Environmental Psychology, Spatial Behaviour and Isovist Properties**

Environmental psychology is a field of research that examines the relationship between individuals and their environment. Within this field, environmental preference theories attempt to combine psychological and spatial factors to explain human experience and behaviour as arising in relation to certain features of the environment. Two of the most known theories of environmental preference are Appleton’s (Appleton, 1988) prospect-refuge theory and Kaplan’s. (Kaplan, 1987) ‘information theory framework’. Both theories seem to combine aspects of Berlyne’s (Berlyne, 1970) ‘arousal theory’. However, they appear to point towards different spatial properties and qualities of the environment as being stronger predictors of environmental preference. These two theories form the basis for the two hypotheses of the thesis (as introduced in section 1.4), namely the hypotheses of ‘spaciousness’ and ‘complexity’. The background behind each theory, the relevant properties and corresponding isovist measures of the two competing hypotheses, are discussed in more detail in this section. Some experimental studies are also reviewed here, which examine predictors of environmental preference and human behaviour in relation to several isovist properties.

For instance, Weiner and colleagues have examined the relationship between isovist properties and the spatial qualities of space and human behaviour, in a series of exploratory experiments. The researchers investigated whether isovist measures capture properties of space that are related to locomotion and spatial experience (Franz & Wiener, 2005). Participants performed well in the navigation task which was to find the “best overview place” and “the best hiding place” in several virtual reality gallery environments. These findings suggest that participants were able to

perceive the size of the isovist. Participants also had to rate the environments based on the qualities of interestingness, pleasantness, beauty, spaciousness, complexity, and clarity. The general outcomes suggest that isovist measures can predict the qualities of spatial experience. For instance, their findings indicate that environmental complexity can be described by jaggedness, clustering coefficient, revelation, and openness ratio (ibid.).

In a subsequent study, the researchers focused on translating spatial qualities such as spaciousness, enclosure, and openness, complexity, and order, into several quantitative isovist measures (Wiener et al, 2007). Wiener et al. commented that “while a separation according to the theoretically independent basic qualities could not be observed in these experiments, the general approach of translating qualitative theories into isovist and visibility graph measurands was clearly affirmed” (ibid.). The spatial qualities of spaciousness, enclosure, and openness, complexity, and order, are psychologically-relevant environmental factors that have been associated with affective responses, preference and exploratory behaviour in theories of environmental psychology. Montello (2007) comments that these theories are closely related to spatial behaviour, experience and affective responses (arousal, preference) and supports the idea that these spatial properties and qualities can be captured by isovist and visibility graph analysis measures. Therefore, theories from environmental psychology seem to “offer a qualified basis for empirically testable hypotheses” (Montello, 2007).

Wiener and colleagues (Wiener et al, 2007) discuss how specific spatial qualities are related to evolution-based theories of environmental psychology. They refer to the work of Appleton and his theory of ‘prospect and refuge’ that is related to the spatial qualities of *spaciousness* and the changes between openness and enclosure (Appleton, 1988 in Wiener et al., 2007). This theory is associated with observations on preference for certain environmental scenes that have a grand vista, spaciousness, and openness (prospect) and/or that are associated with the concept of enclosure or safety (refuge) (Appleton, 1988). The qualities of spaciousness or sudden openness contribute as well to the sense of orientation since “the grand vista can be so engaging that the possibility of getting there and back is not a consideration. By

contrast, lacking such a vista the focus shifts to such practical matters as moving through the terrain without getting lost” (Kaplan, 1987).

On the other hand, another important viewpoint from the field of environmental psychology highlights that “environments that provide increased opportunities for gathering or discovering information allow for improved living conditions including heightened safety. Thus, various spatio-cognitive properties associated with exploration potential (including complexity and mystery) also have an impact on environmental preference” (Dosen & Ostwald, 2016). The information theory framework suggests that the variables that have been found to predict preference, might be related to information processing aspects and immediate emotional responses (affect) (Kaplan, 1987).

Visual complexity, or stimulus complexity in general, appears to influence the level of arousal and, according to Berlyne, it is also related to affective responses such as pleasure (Berlyne, 1970). He argues that high novelty and high complexity may increase the level of arousal because “the initial impact of a complex stimulus pattern can be expected to engender uncertainty, conflict, disorientation”. However, as the degree of novelty decreases, uncertainty and conflict are resolved and “elements are discriminated, classified, recognized, and grouped together as sub-wholes. This can evidently be a source of pleasure, presumably dependent on the arousal-reduction mechanism” (ibid.). The resolution of conflict through chunk decomposition and recognition of the elements, and the arousal-reduction mechanism that leads to pleasure obviously shares some similarities with the underlying processes of the Aha! experience.

The spatial quality of *complexity* is thoroughly discussed by Kaplan (Kaplan, 1987). He focuses on the factor of ‘mystery’ which describes better the element of prediction: moving further into the scene will yield additional information. ‘Complexity’ refers to information that is immediately available while ‘mystery’ is about the promise of gaining new information. He highlights that ‘mystery’ should not be misinterpreted as an example of ‘surprise’<sup>17</sup>, since ‘mystery’ suggest a

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<sup>17</sup> Kaplan refers here to Berlyne's ‘collative variables’ that include surprise, novelty, complexity and ambiguity (Berlyne, 1960 in Kaplan, 1987) and he comments that “A well-crafted mystery allows one



continuity “between what can be seen and what is inferred” which does not trigger a totally surprising experience but is rather more closely related to an “impossibility of complete perception”<sup>18</sup> (ibid.). Within the framework of predictors of preference, the two affective outcomes are *Understanding* (the ease of making sense) and *Exploration* (being attracted towards sources of additional information). ‘Complexity’ and ‘mystery’ fall in the Exploration category because they are related to “information available for further processing”. The category of Understanding includes variables that are related to information that enhances comprehension, namely ‘coherence’ (how ‘things hang together’ at the local level) and ‘legibility’. As Kaplan (1978) describes:

Just as ‘coherence’ allows one to predict and orient within the picture plane (the array that is before one), ‘legibility’ concerns the inference that being able to predict and to maintain orientation will be possible as one wanders more deeply into the scene (ibid.).

These predictors of preference deserve special attention because they add a qualitative perspective to human spatial behaviour and cognition through an evolutionary interpretation of preference. Preference is “an expression of an intuitive guide to behaviour” (Kaplan, 1987). Kaplan (1978) explains that it is a direct and immediate experience that helps to “keep the individual in an environment in which orientation and access to new information can be maintained easily” and it is reasonable to assume that the rapid and automatic assessment of the possibilities that an environment offers (e.g. affordances) result in an ‘immediate affective code’ that guides behaviour (ibid.). The acquisition of new information (Exploration) and its comprehension (Understanding) is what supports the creation and use of the cognitive map or in Kaplan words people are rather “enticed by new information, by the prospect of updating and extending their cognitive maps” and preferences are

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to generate hypotheses, directly parallel to the effect of partial information in an environment. ‘Surprise’, in contrast, is a rather indiscriminating term. One can be surprised by something that happens with no prior warning; the suddenness that is appropriate to the meaning of surprise is quite inappropriate in the case of Mystery”.

<sup>18</sup> This description brings to mind Pinna’s discussion of “amodal wholeness” and “modal partialness” and the emergence of the form of meaning in visual perception (section 1.2.1 & 2.1).

concerned “with the gathering of information on the one hand and the danger of being at an informational disadvantage on the other” (Kaplan, 1987).

Theories from environmental psychology, therefore, suggest that there are two main tendencies regarding environmental preference. The first relates to the psychological factors of prospect and refuge and the spatial qualities of spaciousness and the transition between enclosure and openness. The second is associated with the qualities of complexity, mystery, coherence, and legibility responding to the needs of understanding and acquiring new information. These two tendencies offer the basis for formulating the two hypotheses of the thesis and test in what sort of spaces it is more likely for people to experience the Aha! moment of reorientation. For simplicity, I will call the first one ‘a change in spaciousness’ and the second ‘a change in complexity’; the first one describing the sense of novelty and surprise and the second describing an informationally-relevant novelty.

### **Relevant isovist properties**

Franz and Wiener (2008) explore the relationship between some of these spatial qualities and the isovist properties that may provide an associated quantitative description. Their findings show a strong correlation between the rated spaciousness and the isovist property of area (Franz & Wiener, 2008), which is supported by another study on shape and spaciousness conducted by Stamps (Stamps, 2008). Isovist Area is the area of space visible to from a given point in space. Additionally, Ruth Conroy-Dalton (2001) provides evidence in her thesis that people usually pause to re-evaluate the environmental information and make new decisions on movement and direction at locations where there is novel visual information, which justifies the correlation of these pause-points with high values of isovist area.

The concept of openness, closely related to the idea of ‘prospect’, is rather related to the measure of revelation coefficient. This notion of openness describes the sudden availability of a new and large amount of visual information. And this spatial quality can be described by revelation coefficient, which is a new isovist measure proposed by Franz and Wiener (2008). Revelation is the “relative difference between current neighborhood size [isovist area] and the collective neighborhood size of its directly

adjacent nodes”. High revelation indicates low visual stability, suggesting the element of surprise and novelty (Franz & Wiener, 2008). This measure has been also associated to the notion of ‘place’ and it has been suggested that the total revelation of an area “serves as a powerful measure of the local heterogeneity of a location and hence a place’s identity” and that isovist revelation “may be enough to situate the inhabitant in a space” (Dalton, 2011).

The factor of complexity and mystery, or ‘change in complexity’, seem to be related to the isovist property of clustering coefficient, since this measure describes the ‘spikiness’ of the isovist. It describes the complexity of the environmental shape, which plays a key role in orientation. Franz and Wiener (2005) have also considered clustering coefficient as a measure associated with the complexity of the visual information. It also seems to be related to the perception of objects within spaces. According to Turner and colleagues, it does not only describe the geometric ‘spikiness’ but it is sensitive to the varying size of objects that disrupt the space (Turner et al, 2001). Clustering coefficient describes “how ‘self-contained’ the information in a particular isovist” is, and the relative intervisibility within a neighbourhood. It picks out the changes in visual information as the system is navigated. In graph theory is defined as the number of edges between all the vertices in the neighbourhood of the generating vertex divided by the total number of possible connections with that neighbourhood size (ibid.). That is the proportion of the actual visual connections within the neighbourhood of the current vertex in relation to the number of all possible connections (Turner, 2001b). Low values occur at locations with multidirectional visual fields “where a new ‘area’ of the system may be discovered” (Turner et al, 2001). Turner’s description also suggests that it is possible that clustering coefficient is related to the notion of ‘mystery’ and the promising of new information which is not immediately available.

The ‘coherence’ factor of Kaplan’s information theory is more difficult to be associated directly with a specific isovist property since there is no immediate association in the literature between a specific measure and the local ‘good gestalt’ property. However, one assumption, as we will see in the next paragraphs, is that a combination between high values of the isovist property of ‘visual control’ and low-

mid values of clustering coefficient may be a good candidate for describing this factor of ‘coherence’, of how things ‘hang together’.

Montello (Montello, 2007) makes a very interesting comment on the ‘poor form’ of mazes which makes them disorienting (as opposed to a ‘good’ gestalt form). He points out that mazes are usually characterised by

...path segments that twist and turn in space, but **do not branch**—they actually have no choice-points that require a person to pick which way to go, at the risk of getting lost. That is, [mazes] should not be psychologically challenging or stimulating. Nonetheless, they are quite disorienting, they promote mental states that seem ‘altered’ from our normal waking mental state (Montello, 2007, emphasis added).

His comment highlights the significance of ‘*branching-off*’ locations, of street intersections that offer multiple possibilities for movement. Although these locations are more complex and psychologically challenging, their absence seems to result in disorientation.

The ‘branching-off’ property of junctions has been also explored by Meilinger and colleagues (2012) and its relation to participants performance in spatial tasks. They used several isovist measures, including clustering coefficient, jaggedness, and openness, to study and classify street intersections using Principal Component Analysis. The geometric properties of intersections as captured by isovist revealed a division between two geometrically dissimilar groups: T-intersections and non-T-intersections such as branch-offs, cross-intersections, etc. Participants performed much better in tasks related to route knowledge at the non-T-intersections, even though they had more alternatives to choose from (2.4 on average). This makes the task more difficult and complex to solve by chance compared to the T-intersections. In branching-off situations, participants had to store and recall these directional changes during navigation as opposed to T-intersections, which are “psychologically different from a topologically equivalent branch off” (Meilinger et al, 2012).

Street segments that ‘branch-off’ offer more choices for movement (as opposed to no choice-points or two choice-points) which appears as an important factor for orientation. These locations that have choices of movement and ‘the risk of getting lost’, are more complex and rather stimulating with increased levels of arousal, and thus may result in affective response. It is possible that these locations have an affective quality that could be explained by the arousal-reduction mechanism mentioned earlier (Berlyne, 1970). Clustering coefficient is considered as a relevant measure here since it has been proposed that it captures the ‘junctionness’ of a location (Penn & Turner, 2002), which is most probably what Montello describes as lacking in the case of mazes. On the other hand, locations with choices for movement are quite closely related to the description of the isovist property of visual control (Hillier et al, 1987a). This suggests that visual control might also be a quite relevant isovist measure for the ‘change of complexity’ hypothesis.

Visual control is defined “as the area of the current neighbourhood with respect to the total area of the immediately adjoining neighbourhood” (Turner, 2004). Hillier describes it as “a local measurement of the degree of choice of movement for each space in relation to its immediate neighbours” (Hillier et al., 1987a, p.237). Turner uses the example of the 'Panopticon' to explain that the cells in the periphery lack control relative to the centre which has visual links to many locations (Turner, 2004). Therefore, visual control describes how visually dominant a certain location is in relation to its neighbours. High visual control occurs at visually dominant locations where a large number of spaces can be seen, but these spaces can each 'see' relatively little (Turner, 2004).

Clustering coefficient and visual control appear to have a strong association in this case, but it is difficult to find in the literature a study that focuses on their interrelation. A recent paper on the spatial structures of ants' colonies, gives perhaps an indirect hint about the relation of these two measures through the description it provides of the top-ranked location of the queen's nest (Varoudis et al, 2018). The main area of the queen's nest was reported as having low clustering coefficient values and was associated with the qualities of 'openness' and 'control'. This location offers the queen good local control regarding the “level of immediate accessibility”. On the other hand, the small cavities that are adjacent to the main area have the

highest clustering coefficient values and provide the opportunity for the queen to hide from the rest of the nest (Varoudis et al, 2018). The description of this top-ranked location shares some similarities to the Bentham's 'Panopticon', which is often used as an example to explain the visual control property (Turner, 2004). The differences between the spatial properties of the queen's main area and the adjacent chambers, resemble the ones that can be found when looking at the central location of the Panopticon, where visual control is high, and the cells in the periphery, respectively. Another interesting quality that could be associated with these spatial conditions, is that one can get a more 'coherent' image or a 'good local control' at the centre of then Panopticon than from any of the adjacent chambers.

Both properties of clustering coefficient and visual control are potentially related to spatial behaviour, although the role of clustering coefficient has received greater attention within the relevant literature. Visual control seems to be associated with the evaluation "of choices of movement" (Hillier et al, 1987a) as well as "the degree to which a space is better or worse connected than its neighbours" (Hillier et al, 1987b). The evaluation of choices of movement might be associated with attentional load and spatial working memory demands. In addition, the quality of visual dominance in relation to the adjacent locations offers a greater understanding of the local field than any other neighbouring location could offer. Visually dominant locations, where there is a higher degree of choice for movement in relation to the immediate neighbours, may promote a sense of understanding of how 'things hang together' at the local level. Therefore, it is possible to consider that these locations might be associated with the factor of 'coherence' of the complex scene, which according to Kaplan is a predictor of preference (Kaplan, 1987). Clustering coefficient has a more direct association with wayfinding because it picks out variation in visual information during movement. In addition, low clustering coefficients occur where a new 'area' of the system may be discovered (Turner, 2001). This promise that further exploration of the environment will lead to the acquisition of new visual information, suggests its relation to the psychological factor of 'mystery' as described in environmental psychology.

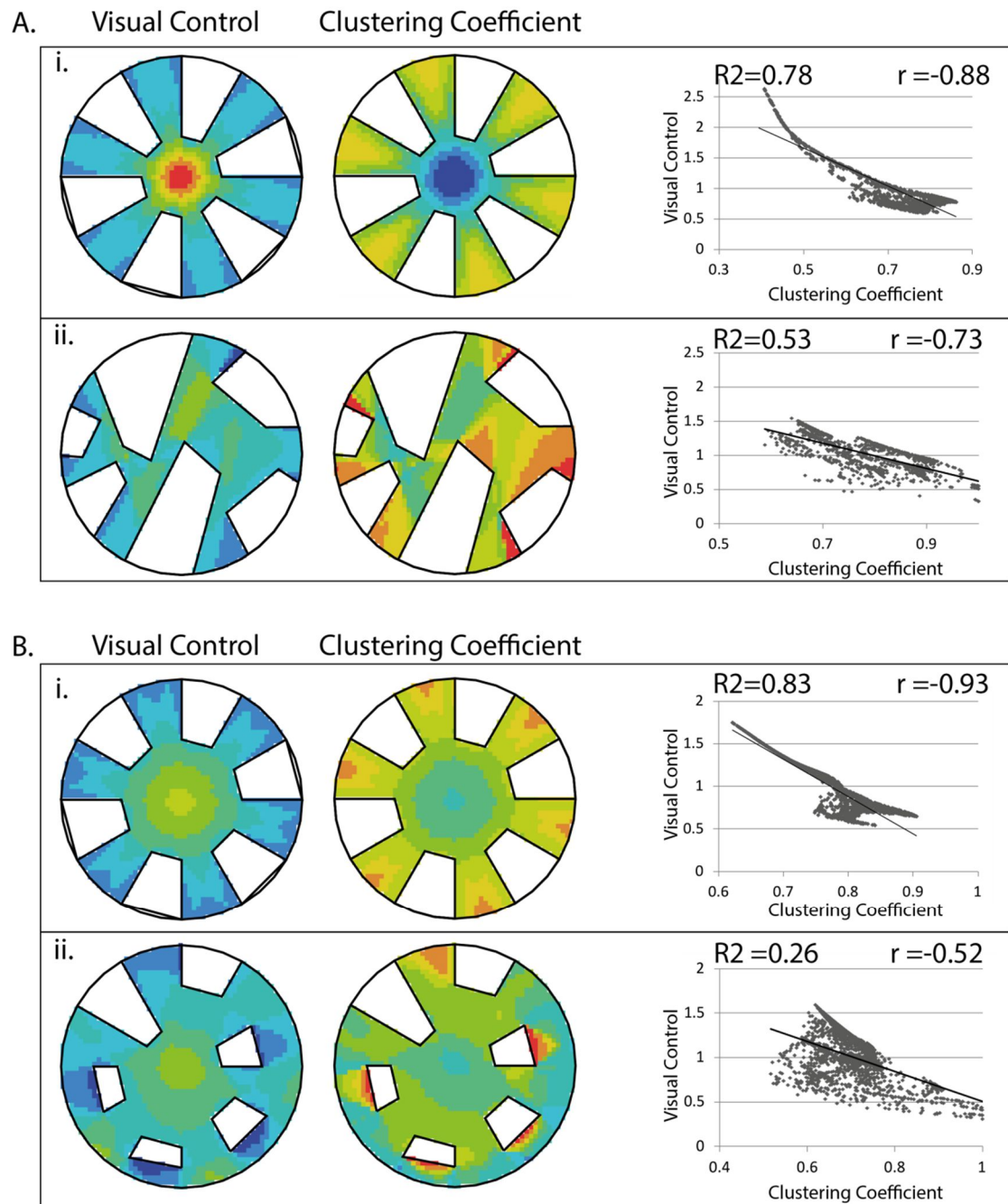


Figure 2.3-1. VGA of radial space diagrams and correlations of visual control and clustering coefficient Isovist values of clustering coefficient (first column) and visual control (second column). Correlations of the two measures (third column). The first row in both cases A and B shows a clearer radial pattern. The second row in both cases A and B shows a more irregular pattern.

The series of radial space diagrams in Figure 2.3-1 explores the relationship between these two measures. I have selected radial spatial pattern to investigate the correlations between these isovist properties because this configuration is close to the idea of the Panoptic, which is used to describe the visual control measure but is quite close to the concept of the clustering coefficient as well. These diagrams show the

distribution of visual control (left column) and clustering coefficient (right column) values and the third column shows their correlations in each case. In both A and B cases (Figure 2.3-1), the first row shows a clearer pattern of ‘branching-off’ rather closer to the idea of ‘good form’, while the second row shows a more irregular almost random pattern. The two isovist measures appear to have negative correlations in all these cases. However, the first rows of both A and B cases (Ai and Bi) have greater negative correlation as indicated by the  $r$  values of Pearson Correlation ( $r=-0.88$ ,  $r=-0.93$ , respectively). In contrast, in the cases of the more irregular patterns (Aii and Bii), the values do not exhibit such a strong correlation ( $r=-0.73$ ,  $r=-0.52$ , respectively). Thus, in the cases where the pattern is more clear (first row) and resembles a street intersection (branch-off) the values of visual control and clustering coefficient are highly correlated.

In addition, a significant difference between the two measures can be observed in Figure 2.3-1 Bii. In diagram Bii, some of the 'built' parts of diagram Bi are replaced by smaller object-like built chunks that permit the emergence of intervisibility relations at the regions of the periphery. Visual control values (Figure 2.3-1B ii, first column) seem to preserve a distribution that is more even when going from the centre towards the periphery (a smooth reduction of the values). Clustering coefficient (Figure 2.3-1B ii, second column), on the other hand, appears to have values trending towards the low end of the spectrum, both at the centre and periphery but with an increase near the 'objects' (forming a sort of a green-yellow ring).

Both isovist properties include in their input parameters, measurements of the area of the generating isovist and the area of the adjacent isovist. However, their difference lies in the way they calculate the ratio between generating and the adjacent isovist. The observed differences in Figure 2.3-1 Bii may be due to the fact that the property of visual control does not take into account the relation between the neighbours of the generating isovist and thus the centre has a greater effect on the distributions of the property's values. On the other hand, the clustering coefficient measure takes into account the actual intervisibility between the neighbours in relation to an “ideal” total intervisibility and: “any pair of mutually visible locations within the isovist area contribute to the overall value” (Turner et al, 2001). We could say that clustering coefficient represents local triangulation relations as 'visibility loops' (ibid.). Thus, it



seems to be a kind of a local 'allocentric' measure, since allocentric navigation "is essentially a geometric triangulation process" (Buzsaki, 2005) as opposed to a more 'centre-based' visual control. Perhaps the strong negative correlation of these values especially in the 'branching-off' diagram of the first rows in Figure 2.3-1A and B suggests that the combination of these two properties might reflect the quality of local 'coherence' of a certain location and low values of clustering the sense of 'mystery' since, according to Turner, they are related to the discovery of new areas of the system through further movement (Turner, 2001).

Isovist properties and visibility graph analysis, provide the tools for the context-based analysis in the experimental paradigm of the thesis, since they appear to correlate with individual behaviour and spatial experience and they are suggested as appropriate techniques able to capture evolutionary-based spatial qualities (Conroy, 2001; Franz & Wiener, 2005; Franz & Wiener, 2008; Montello, 2007). The virtual reality experiment is focused on the moment of re-orientation and permits the investigation and comparison of the two possible spatial 'situations' that may trigger the Aha! experience (Chapter 3). These are based on theories of environmental psychology of 'prospect and refuge' and Kaplan's framework of predictors of preference. The 'spaciousness' hypothesis suggests that a *change in the amount of visual information* may engender the Aha! moment, as opposed to the 'complexity' hypothesis that suggests that the *change in the complexity of the visual information* is a stronger predictor. Therefore, the behavioural and EEG analyses (Chapter 4) of the data collected in the virtual reality experiment are focused on the relevant isovist properties associated with these cases, which are: isovist area and revelation for the '*change in spaciousness*' hypothesis, and clustering coefficient and visual control for the '*change in complexity*' hypothesis. The objective is to test which of these theories may engender the affective response and experience of the Aha! moment.

## **CHAPTER 3      Methodology**

### 3.1 Introduction

The thesis adopts a trans-disciplinary methodological approach and combines spatial analyses with behavioural analyses and EEG recordings (electroencephalography). In other words, the spatial properties of the environment are investigated in conjunction with individual responses at the neural and behavioural level. The visuospatial properties are quantified, as discussed in sections 3.7.1, through the use of isovist and visibility graph analyses (for more details see sections 2.3.2 and 2.3.3), and are examined in relation to EEG recordings that are acquired from the Emotiv headset (section 3.4), which is a wireless EEG system.

The objective of the virtual reality experiment is to investigate the moment of self-localisation after disorientation and the Aha! effect of recognizing where one is. That is when subjects recognize their location in relation to their surroundings. The Aha! effect is isolated based on the participants' responses. Participants' responses to the task indicate that they have passed from a state of not knowing to a state of knowing, of being aware, of their current location (the Aha! effect). However, the event of interest is not exactly the moment that participants give their response but an event that precedes that, which is a spontaneous action-related response of the virtual 'body'.

For example, disoriented individuals coming out of the tube will follow a certain direction of movement but upon realizing that this direction is wrong they will stop and change the direction of movement. Spontaneous backtracking was also observed in a recent experiment on goal-directed navigation (Spiers 2018) where, in 80% of the cases, the change in the course of action resulted in decreasing the path distance to the goal. The moment there is a change in participants' course of action (movement), just before their response to the task, is most likely closely related to the spatial Aha! experience. Therefore, the event of interest for the analysis of the behavioural and EEG data is the moment that participants take their finger off the forward movement button (up arrow), which is a salient psychological moment. Thus, the button-release moment is when they decide to stop their virtual movement at the specific location where they finally give their response. A change in the course

of action such as stopping the movement (just before the response) is an indication that a change has occurred.

To identify the timescale that would allow us to study the related brain dynamics, we need to know the time window in which any relevant cognitive processes may occur. A study focusing on working memory during wayfinding suggests that encoding processes of significant decision-points during route learning takes place three seconds before passing that point location. The researchers of this study looked at participants' performance on a secondary verbal task before, during and after crossing intersections that should be remembered for a subsequent wayfinding task. They reported that participants' performance on the verbal task was at its lowest, at about three seconds before passing the middle of an intersection (Meilinger, 2008). Consequently, both behavioural and EEG analyses are mainly focused on changes between time-periods of three-seconds duration (3s epochs).

This chapter explains in detail the methodology used in the thesis. After a brief introduction focused on the EEG signal, the chapter explains the recruitment and data acquisition processes, the design of the virtual environments, and the experimental procedure. The last sections are focused on the data analysis, the EEG signal processing steps, and the statistical analyses.

## **3.2 The EEG signal**

The electroencephalography (EEG) is a relatively inexpensive method for recording electrical signal from the human scalp. It is the result of firing activity of a large population of neurons. A more formal definition would be that the "EEG reflects mainly the summation of excitatory and inhibitory postsynaptic potentials at the dendrites of ensembles of neurons with parallel geometric orientation" (Cohen, 2014, p.52). The electrical field is powerful enough to be recorded by scalp electrodes only if it is the result of several hundred or thousands of neurons firing synchronously. Scalp EEG electrodes usually require the use of a gel or salt-water-soaked sponges (e.g. Emotiv) in order for the electrical signal to be transmitted from the scalp to the electrodes (Cohen, 2014, p.52-60).

The EEG, therefore, directly measures the neural activity at the level of the population of neurons. It cannot capture all neural events but, according to Cohen, no brain-image technique can really do that (Cohen, 2014, p.52-60). The EEG technique is an advantageous tool because, due to its high temporal resolution, it can capture cognitive dynamics "at the time frame in which cognition occurs", which is tens to hundreds of milliseconds (Cohen, 2014). There is empirical work that supports the causal role of neural oscillations in cognitive processes but this is still an issue of debate. Evidence suggests that electrical fields have a causal role in neural computation and the transfer of information. For example, hippocampal long-term potentiation (a long-lasting increase in the synaptic strength of the neural cells), which is related to memory formation occurs at specific phases of the theta band (Cohen, 2014). Also, the synchronisation of oscillatory activity between different regions of the brain is thought to be a mechanism that supports the transmission of information across neural networks and, thus, supports perceptual and cognitive processes (ibid).

One limitation of the EEG technique is that it is difficult to record activity from deep brain structure, as for example, the hippocampus. Also, in order for the electrical field to be powerful enough to reach the scalp, it is not only necessary to have a synchronous activity of a large population of neurons but these neurons should also fire towards the same direction, otherwise they cancel each other out. Another limitation of the EEG technique is that it has a low spatial resolution. That means it is difficult to find a unique brain source for a given EEG signal. Nevertheless, there are techniques and methods for source localisation that have been developed (e.g. using ICA).

### **EEG signal processing**

The EEG signal can be conceptualised as a change in voltage of the electrical signal over time and space since it is recorded by different electrodes, which are placed on specific locations on the human scalp. The EEG is a time-dependent signal with a very high time-resolution and can be processed in the time-domain or in terms of frequency bands (e.g. delta, theta, alpha, beta, gamma). The time-domain analysis, using the event-related potential methodology (ERP) has the advantage of a simple

and fast method of analysis with high temporal precision (Cohen, 2014). The decomposition of the signal into different frequencies can be done by using various methods of time-frequency analyses. Thus, changes in the EEG power at different frequency bands can be investigated and compared between different conditions. The EEG signal is, therefore, multidimensional, and besides being studied in relation to time and space, it can be studied in terms of frequency, power, and phase. Frequency refers to the 'speed of the oscillation' measure in hertz (1Hz is one cycle per second), power refers to the strength of the frequency band activity, and phase is the timing of the activity (Cohen, 2014).

Spontaneous EEG activity can be analysed in relation to different experimental conditions. When the EEG data is used to assess the neural responses associated with a specific internal (cognitive task), external (stimuli) or motor event, the focus is on the pre- or post-event signal. In this case, researchers can analyse the event-related potentials (ERP) in the time domain or event-related spectral perturbations (ERSP), which show the shifts in the power spectrum in time-frequency analysis (*ibid.*).

ERPs are small changes in voltage triggered by an event. Positive (P) and negative (N) deflections in the waveforms reflect the flow of information through the brain. (Luck 2005). Different conditions within an experiment may elicit distinct cognitive responses that are reflected by differences in amplitude and latency in the respective waveforms. The P300 or P3, for instance, is the third positive deflection in relation to the onset of a stimulus – and usually 300ms after – and its amplitude has been related to attentional load and cognitive effort (Luck 2005).

The signal of interest, the evoked-response, is usually obscured by the much larger EEG spontaneous activity and the averaging technique is used to cancel out this noise. The continuous EEG signal is marked with event-codes and is segmented into epochs that are time-locked in relation to the specific event. Random bio-signals such as eye-blinks and muscle artifacts can be detected by visual inspection or by using artifact detection algorithms (e.g, peak-to-peak function). Trials contaminated with artifacts are usually either rejected or marked and excluded from further processing. However, a more effective alternative is the use of artifact correction procedures that minimize the rejection of valuable trials. For example, ICA-based

artifact correction (Independent Component Analysis) can be applied to the data in order to decompose the data into a set of underlying components, remove certain components that correspond to artifacts and then recompose the data without those artifacts (Lopez-Calderon & Luck, 2014). The event-unrelated noise is cancelled out by averaging together a big number of epochs from the same individual, which contain the event-related signal of interest. The final ERP waveforms are a result of a grand average of epochs across subjects, one for each electrode and each experimental condition.

The ERPs ‘reveal a fraction of that multidimensional space’ of the EEG signal and there are cases where brain dynamics related to a specific task can be lost during ERP averaging (non-phase locked activity). Although the time-frequency based approaches require more complicated levels of analysis, they offer a better tool that enables the association between findings from several disciplines within neuroscience (Cohen, 2014, p.22). Time-frequency decomposition of the EEG data can be achieved by applying signal processing techniques to separate the brain rhythmic activity into different frequencies. In this way, changes in EEG power at certain frequency bands and brain dynamics that are assumed to be associated with the Aha! moment (based on the literature of different relevant fields) can be studied in relation to the spatial properties and participants' decision to give a response to the task.

### **3.3 Subjects and Recruitment Method**

Data were collected from twenty participants (9 female) with an average age of 33 years (min=20, max=43). Participants were right-handed with normal or corrected-to-normal vision and none reported any history of psychiatric or neurological problems. Two participants were recruited from the PALS Divisional Subject Pool in exchange for course credit and the rest responded to email advertisement and participated voluntarily. Half of the participants had a background in a spatial design or spatial analysis related discipline (e.g. architects, geographers). The research was approved by the ethics committee at University College London and all participants gave their informed consent.

### 3.4 Data Acquisition

Participants' electrical brain activity was recorded using the Emotiv headset (Figure 3.4-1). and the EEG data were collected via a Bluetooth USB chip and saved using the Emotiv Testbench software. The Emotiv headset is a wireless EEG system with 14 electrodes arranged at specific scalp locations. This affordable Brain-Computer Interface (BCI) system is often used to enhance user's gaming experience, but the device has also been reliably used for scientific explorations (Badcock et al, 2013). The Emotiv Software Development Kit includes three implemented applications (Expressiv, Affectiv, and Cognitiv Suite) which process on-line information of brain activity, as well as muscle movement artifacts, in some cases using machine-learning algorithms. Even though these Suites provide the means for a good gaming experience, the exact details of the underlying algorithms are not available to the user. Thus, their ambiguous “black box” nature makes them unreliable for scientific research. However, the Research SDK package includes the Emotiv Testbench, a software tool that allows researchers to access and record the raw EEG signal<sup>19</sup>, insert time-markers in the data stream and export the data for further processing. This option offers a reliable and appropriate method of data acquisition.

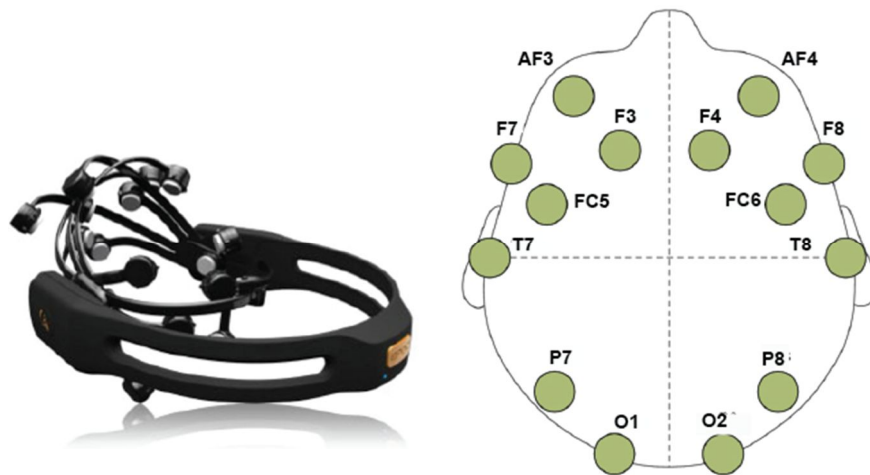


Figure 3.4-1. The Emotiv headset and electrodes location

<sup>19</sup> The EEG is sampled by the hardware at 2048Hz and then down-sampled to 128Hz (128 data points for one second). The device applies a pass-band filter to the signal to remove frequencies below 0.16Hz and above 85Hz and a notch filter at 50hz and 60hz to remove artifacts produce from the power line.



A conventional desktop VR setup was used for this experiment. This allowed all participants to complete the tasks without experiencing any motion sickness, which is often observed when using VR headsets. The same computer was used for the virtual navigation and for EEG recordings in order to have more accurate timing of the keystrokes, as event-markers in the recorded data stream (Figure 3.4-2). Event code triggers, generated by the game engine, were recorded by the Emotiv system (Testbench software), via virtual serial ports, in order to synchronise EEG activity and behaviour. During each trial, participants' position, within the virtual reality urban environments, and heading direction, were recorded into a log file every 0.25 seconds.

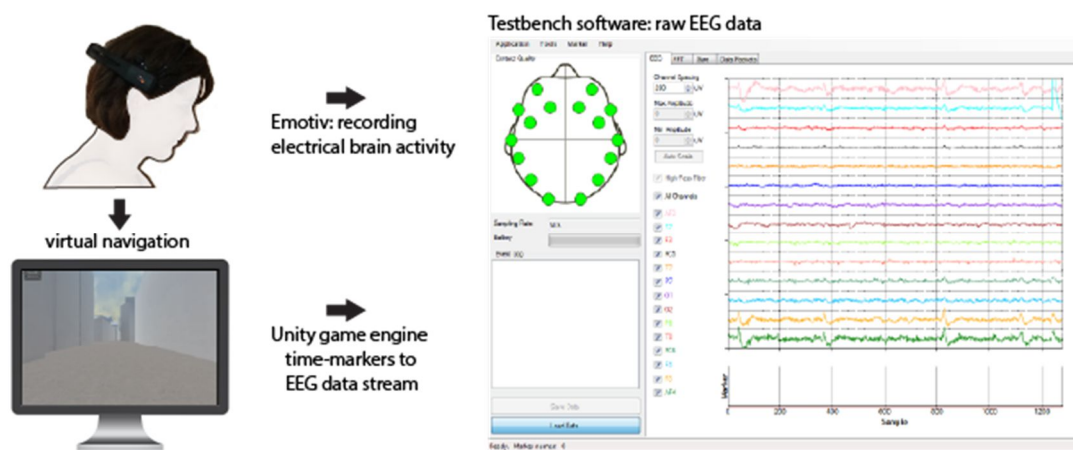


Figure 3.4-2. Data acquisition.

### 3.5 The Virtual Reality Environments

The virtual reality urban environments used in this experiment were created and developed in the game engine Unity3D (version 5.3.4), with three-dimensional urban models created with Rhino3D. The virtual environments in figure 3.3-1 represent real urban regions from three different European cities which were slightly changed or mirrored in order to reduce differences in the degree of familiarity with each environment across participants. In addition, in order to prevent participants from orientating based on the direction of light within the virtual environment, the

buildings do not cast any shadows on other buildings or streets and there is no visible sun that could act as an orientation cue. The three environments do not differ significantly in terms of their spatial configuration, and they all include distinct sub-regions and grids of different orientations.

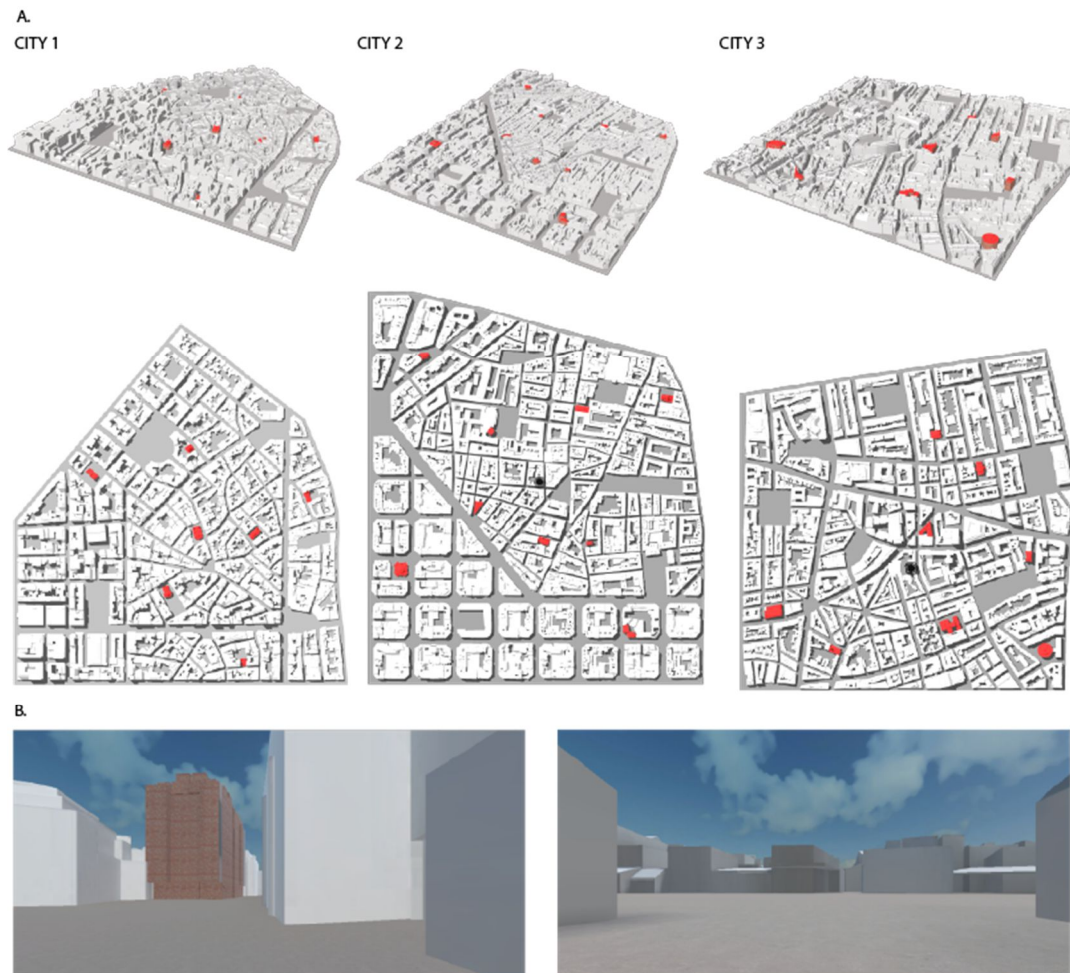


Figure 3.5-1. Maps and perspective views of the three virtual reality environments. The bottom row shows vistas from the participant's point of view. Landmark-building (left) and urban square (right).

Each environment contains landmarks in random locations, several urban squares and grids with different degrees of complexity in order to facilitate participants' orientation. Landmarks in the virtual environment appear as buildings of a brick texture whereas the rest of the buildings appear in grey colour (Figure 3.5-1 B). The landmark-objects in this paradigm are randomly-placed, visually-salient buildings, and can only be perceived at a local level. Therefore, they cannot be perceived from a distance (which usually facilitates orientation) and the possibility of forming

constellations is reduced by the fact that they cannot be perceived simultaneously. Furthermore, they differ in terms of colour and texture, in relation to the other buildings which are just grey; however, they all share the same visual attributes and are only slightly different in shape.

### 3.6 Experimental Procedure

The duration of the experiment was about 1.5 hours on average. Prior to the experiment participants were verbally informed about the structure of the experiment and the task. The Emotiv (Testbench) headset was then placed on their head in order to record EEG activity throughout the duration of the task. Because movement causes noise artifacts to the EEG data, participants were specifically asked to stay as still as possible during the experiment. Although think-aloud protocol could have been revealing, especially in identifying the Aha! moment, jaw movements, in particular, cause great artifacts. Therefore, participants were instructed to avoid speaking during the recordings. To navigate the urban environment participants were instructed to use the navigation keys (e.g., arrows for up, down, left, right). Speed was fixed when the key with the arrow indicating up was pressed and participants could release it to pause movement. In order for participants to become comfortable with the task, they were first familiarised with the instructions and procedure in a simple urban training environment with a grid of 4x5 similar building blocks, one urban square and one landmark (Figure 3.6-1).

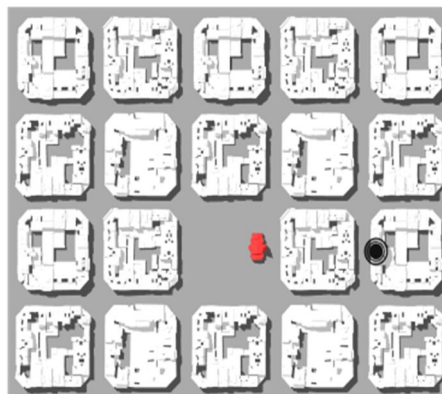


Figure 3.6-1. Map of the training environment. The red building represents the landmark and the black dot the starting location.

Each participant was asked to complete 8 trials in each environment (three sessions), giving a total of 24 trials for analysis per individual (8 trials x 3 sessions). Before the start of each session, the instructions were again presented on the screen as bullet points. The rationale behind the design of this experiment is that participants need to have initial map-based knowledge of the urban region, thus, they are asked to study the map of the specific environment prior to their exploration. This offered participants some initial form of spatial knowledge, which is allocentric. They then explored the environment until they were able to recognise where they were in relation to the map. Each session of the experiment was divided into two stages, comprising a study (Figure 3.6-4) and a test phase (Figure 3.6-3):

a) *Study phase*: At the beginning of each session a map of the city region was presented on the screen. Participants were asked to carefully study the map and memorise the layout of the whole area, rather than the location and relation between landmarks since these would often not be visible. Participants were specifically instructed to focus on the spatial layout and not the landmark locations since the objective was to assess the role of the spatial properties. The study phase did not have any time limit and participants were asked to press the spacebar as soon as they were ready to proceed to the next phase.

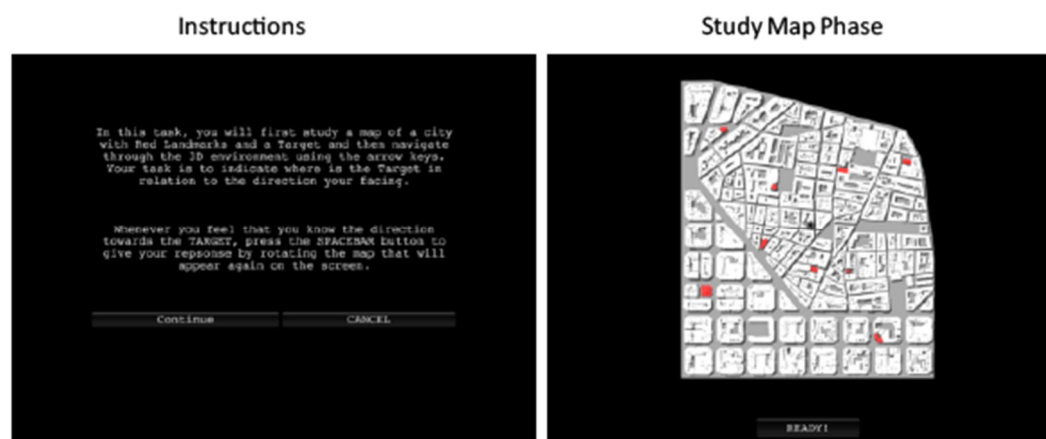


Figure 3.6-2. Study phase: Beginning of each session

b) *Test phase*: Participants' tasks were to explore the environment until they had the feeling of knowing their location in space and were thus able to orient themselves in relation to the map presented in the study phase. At this point, they were instructed to press the spacebar on the keyboard in order to give their response.

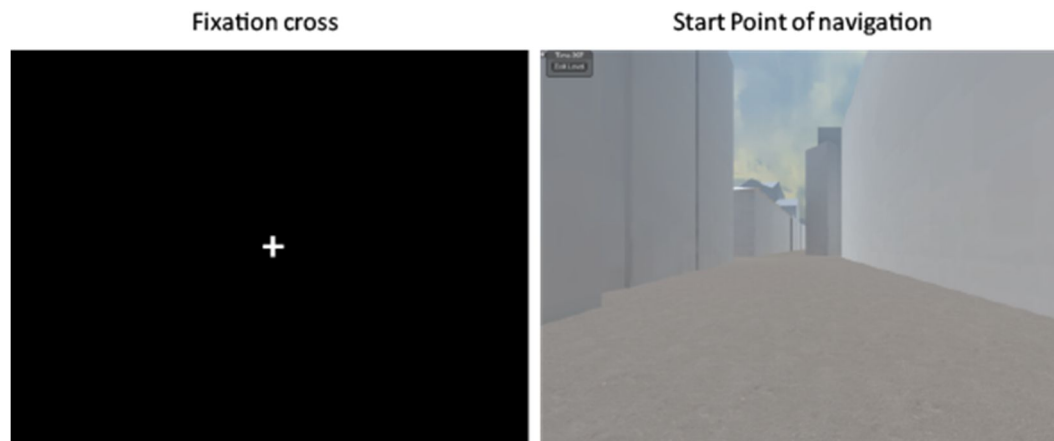


Figure 3.6-3. Test phase: Beginning of each trial.

Participants were encouraged to give a response as soon as they first had the feeling of knowing where they were. Pressing the spacebar activated a graphic user interface (GUI) shown in Figure 3.6-4, which appeared on the screen. The GUI included an image of the map of the environments, a slider with 3 levels, and a 'save response' and 'exit' button. Subjects were asked to rotate the map on the screen (using the mouse) and align it with their heading direction (a common action that is performed when we use physical maps). They were asked to rate their confidence regarding this response using the slider (3= 'certain', 2='probably right', 1='not sure'). Then, they had to save their response (using the 'save response' button at the bottom of the GUI) within 40 seconds, otherwise, the GUI would disappear. After saving their response they were instructed to press the 'exit' button at the top left corner of the interface. At the end of each session, their score (percentage of correct responses overall response) appeared on the screen.



Figure 3.6-4. Graphic user interface allows participants to give their response. Participants were instructed to rotate the map and align it with their heading direction (using the mouse), rate their confidence regarding their response (using the GUI slider) and save their response.

Data regarding the spatial abilities and properties of the individuals were collected at the end of the experiment task. Participants' spatial abilities and subjective sense of direction were assessed using the Santa Barbara Sense of Direction (SBSD) self-reports with a scale from 1 to 7 (mean=4.67, min=3.33, max=6.47). The SBSBD test is a subjective assessment of the sense of direction, and, thus indicates as well how confident one is in their ability to navigate and orient in space.



Figure 3.6-5. Starting point locations (in red)

Each trial (8 for each session) began from a different, random starting location (Figure 3.6-5), thus placing the participant in an initial state of disorientation. The objective of using this experimental task was to simulate a real-world scenario where

individuals pass from a state of being lost and disorientated (conflict of misaligned frames of reference) to a state of being situated in relation to space (i.e. the map representation) and re-orientated. For example, you may study the map of an unfamiliar city you are visiting but forget to take the map when you go out to explore the new urban environment and end up getting lost. Or imagine you are a tourist in a new city, coming out of the tube station not knowing where you are and you need to find the direction towards the hotel. Not having enough battery on your mobile phone, the natural thing to do is switch on the map application once you arrive at a location where you feel a sense of familiarity. In these situations, there is a distinct feeling when you suddenly find yourself in a place that seems familiar or an even stronger feeling when you suddenly think you actually know where you are.

### **3.7 Data Analysis**

The objective of the analysis is to isolate the effect of interest and examine where it is more likely for these spatial Aha! moments to occur. Participants start at a state of disorientation in relation to the large-scale environment and during their exploration within the virtual environments, they presumably search for spatial cues. Their task is to respond when they have a feeling of knowing where they are. The focus of the analysis is on the moment when participants spontaneously change their course of action just before they give their response (button-release moment). This suggests that the spatial configuration at the specific location where this happens has an immediate effect on the movement of the body. In addition, it is likely that the button-release response is facilitated not only by the spatial properties of the final location, where subjects give their response but by sudden transitions of the perceived visuospatial information just before that moment; that is, a sudden change in the amount or the complexity of the visual information that precedes the button-release moment. Therefore, there are two events of interest that drive the analyses: (1) moments when the visuospatial information changes suddenly in the time preceding the button-release (up to 3s); and (2) the moment when participants release the movement button to respond to the task, since they believe they have oriented themselves. The specific behavioural effect, the button-release moment, enables the investigation of the mental event of the Aha! experience in relation to a context-based analysis.



### 3.7.1 Spatial Analysis

Isovist analysis was used to quantify the visual properties of each environment. As explained in section 2.3.2, the isovist method provides a quantitative technique to formally describe and compare different locations in terms of the quantity, change and distribution of visual information (e.g. area, perimeter length, length of radials, etc.). The technique of the Visibility Graph Analysis (VGA), developed by Turner and colleagues (2001), adopts measurements from graph theory to calculate the intervisibility of multiple observation points distributed in a regular grid over the whole environment. The analysis of the physical properties of space in terms of the distribution of visual information (using VGA) can offer objective measurements about spatial properties that are related to human spatial behaviour and experience.

In this experiment, isovist and visibility graph measures of the three urban regions were calculated using the Depthmap software on a three-by-three-meter grid covering each environment. The revelation measure (section 2.3.3) is not included in the isovist properties of Depthmap. Therefore, I wrote a python script in Depthmap to calculate this property as the sum of all the differences between the area of the generating isovist and that of the adjacent nodes divided by the area of current isovist, and by the number of nodes adjacent to the origin node. This approach follows Dalton's approach of sRevelation (Dalton, 2011, p78). The output of the VGA analysis, that is, the isovist properties at each grid cell of each environment was saved in a text file. This way, the values of different isovist properties can be linked to each point location of participants' paths in each trial.

### Exploratory behaviour and isovist paths

The log file of participants' position (every 1/4 second) was used to plot these data against the map of each environment to illustrate participants' movement patterns (paths in each trial, location, and duration of pauses and locations of responses) for visual inspection. In addition, a new file was created, which combined the data of the movement-related log file and the isovist values of the Depthmap file. This way, the 'visual rhythm' of participants' exploratory paths can be visualized by unfolding the isovist values along each path (isovist paths).



Isovist paths show the changes in the amount and distribution of visual information along each route and provide a good tool to inspect the changes in relation to an event. This idea was first introduced by Conroy (Conroy, 2001) as a way to study different metrics along a path. They offer a graphical representation of the changes that an individual can perceive in each route. Any pattern of negative or positive peaks, for example, a “crescendo effect due to the increasing visual openness” (Morello & Ratti, 2009), might be related to specific behavioural or mental responses. The isovist path charts show the value of each property (vertical axis) at distinct point locations along each path (horizontal axis). The isovist paths of the trials of a single participant in one virtual environment are examined here in relation to specific time-interval and distance-segments. Because the isovist path analysis is done here just for exploratory purposes, I have used isovist with a visual field of 360 degrees rather than the partial isovist where the visual field is restricted to 90 degrees.

### **3.7.1 Behavioural Analysis**

#### **Performance**

All responses with an angular deviation up to 30 degrees were classified as correct, following the approach adopted in similar studies focusing on alignment effects (Meilinger et al, 2014). Incorrect responses included those with an angular deviation greater than 30 degrees and the no-response cases where participants did not save a response (they pressed the button to exit from the map GUI interface) or failed to respond within the available time limit. Trials where participants entered a building block by mistake or where problems emerged with the game engine during testing were excluded from the analysis.

The mean confidence rating of participants is compared between correct and incorrect responses and the mean angular error of each participant is compared across the three levels of confidence rating (1='not sure', 2='probably right', 3='certain'). Also, other factors that might influence response accuracy are also explored such as individual differences (age, professional background, gender and differences in spatial abilities as measured by the SBS test), heading bearing from North at the final location (which is the orientation of map during study phase), trial

duration, and distance travelled during each trial. In addition, the last part of the analysis investigates the contribution of non-geometric factor and compares the mean duration, mean distance travelled, and mean reaction time<sup>20</sup> of each participant between trials where a landmark was seen versus trials where no landmark was seen.

### **Isovist properties driving spatial re-orientation**

While participants explore each virtual environment, they most likely search for environmental cues that will help them understand where they are in space. To examine what kind of spatial cues contribute to and drive the moment of spatial re-orientation, the analysis explores the transitions of the perceived visuospatial information preceding the button-release moment. The focus is on the peak values of each isovist property in each trial. Based on the hypotheses, these are: maximum revelation, maximum area, maximum visual control, and minimum clustering coefficient. Peak isovist values are averaged separately for each participant and each of the four time periods of equal duration (3s) that precede the button-release moment (12s-9s, 9s-6s, 6s-3s, and 3s-0s).

At this initial stage of analysis, data were also assessed according to distance because participants' speed is not controlled and varies between trials. Thus, the same analysis was done based on segments of distance travelled (60m-45m, 45m-30m, 30m-15m and 15m-0m) until the button-release moment in order to unpick any issues of variability in the mean peak isovist values that might be associated with speed differences. The length of the distance segments was determined based on the mean speed of participants during the 3s-0s time-period.

The analysis is then focused on the differences in mean peak isovist values between the two time periods closer to the button-release moment (6s-3s and 3s-0s). The relative variability of peak isovist values during the 3s-0s period in single-trial data is also examined. In other words, the coefficient of variation of isovist values (the ratio of the standard deviation to the mean) is compared between the four isovist properties of interest.

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<sup>20</sup> Reaction times refer to the time interval between the button-release moment and the moment participants pressed the spacebar to rotate the map and give their response to the task.

### **Frequency distribution of button-release responses**

The next part of the behavioural analysis is focused on the spatial properties of the button-release location and examines where individuals tend to stop more frequently in order to give their response to the orientation task. The frequency distribution of the isovist values at these locations may reveal whether participants' decision to stop occurs at random locations or at locations that support one of the two competing hypotheses. Thus, it shows where it is more likely for participants to recognize where they are. Because participants may use both route knowledge and survey knowledge (knowledge acquired during the study-map phase of the experiment), the population of isovist values in each route and in each virtual environment are used here as references. Trends in the distribution of the isovist values at the button-release location are studied in relation to: (a) the population of point locations of the whole route that each participant has travelled during the trial, until that moment (thus, relevant to the spatial knowledge acquired through movement); and (b) the point locations of the whole system related to the spatial knowledge acquired from figural space, during the study phase of the map.

### **Isovist properties as percentiles of the whole route path in each trial**

For the route-related frequency distribution, the isovist values at the button-release location are normalised in relation to the maximum value of each route ( $x/\text{route max}$ ). The isovist values of all point locations which had been traversed through movement in each trial are divided into 10 percentile ranks with an equal number of point locations in each bin. Therefore, we can study the trend of the values at button-release locations and whether a high percentage of them falls below or above a certain decile.

### **Isovist properties as percentiles of the whole system**

To examine the frequency distribution of the isovist properties at button-release locations in relation to the whole system, the isovist values are normalised in relation to the maximum value of each city ( $x/\text{city max}$ ). Following a similar way of analysis, values of isovist properties in each environment are divided into 10 percentile ranks, with an equal number of point locations in each bin. This analysis

highlights the kind of locations that participants pick up as more important from the population of point locations of the whole system (city environment). Perhaps, it also gives an idea of what kind of local spatial properties seem to be more salient within the representation of the spatial knowledge acquired during the map study phase.

### **3.7.2 Analysis of brain dynamics**

As mentioned at the beginning of this chapter, there are two events of interest: the moments of sudden environmental change preceding the button-release just before the response (stimulus-related analysis) and the button-release moment (response-related analysis). The sudden changes in isovist values just before participants' decision to stop will likely contribute to the update of the representation, and, the spatial properties at the location where participants stop to give their response will likely facilitate the recognition-related processes that will lead to the Aha! effect. To analyse these two events, I adopted two different approaches: in the first case, I used the environmental information to investigate the change in power of the EEG signal, and in the second, I used the change in EEG power to investigate the environmental correlates.

#### **Stimulus-locked epochs**

The event of interest of the stimulus-related analysis is the sudden change in the visuospatial information, as measured by the isovist properties of revelation, area, clustering coefficient, and visual control, in the time preceding (3s) the response-related button-release. The maximum positive change in the properties of revelation, area, and visual control and, in the case of the clustering coefficient, the maximum negative change, are the time-locking events. Epochs of 3s duration are centred around these events. Thus, each individual stimulus-epoch is associated with a change in the value of the relevant isovist property. These changes in isovist values have a different magnitude in each case. To examine the brain's response to these changes, I divided the data set into two categories based on whether the peak change falls above or below the median, which was calculated by taking into account all individual trials.

The stimulus-locked epochs are analysed in the time-domain and the time-frequency domain. To study the event-related potentials (time-domain), the EEG signal of the 3s epochs time-locked to the environmental change is averaged separately for each participant and each condition. A visual inspection of the grand average waveforms (average of all participants for each condition) shows in which channels and time-windows there are significant differences in the event-related potentials (ERPs). The time-frequency analysis is focused on the delta/theta power over the frontocentral channels. According to the literature, theta oscillations typically occur at a lower frequency during virtual navigation peaking around 3.3Hz (Bohbot et al, 2017; Jacobs, 2014) and researchers tend to investigate both low (2–5 Hz) and high (6–9 Hz) theta frequencies (Bush et al, 2017). Thus, the focus here is on the frequencies of 2Hz to 8 Hz which includes both delta and theta bands. The relative change in mean EEG power is calculated by subtracting the mean EEG power of a 3s time-period preceding the stimulus-locked epoch from the mean EEG power of the stimulus-locked epoch. Changes in mean EEG power between the 3s period of interest and the 3s before that are averaged separately for each participant and condition. Average changes in mean EEG power are compared between these two conditions of environmental change for all four isovist properties.

### **Response -locked epochs**

The response-related analysis is focused on the moment of the button-release response and the spatial properties at this location. Participants may release the movement button to stop for several reasons. Other than the decision to stop because they are able to recall information from the map, and thus they want to respond to the task, they might stop because they have a feeling of familiarity or because they have detected some kind of novelty in the environment and want to check the map on the GUI interface. In these latter cases, participants' decision to stop their movement just before they activate the GUI interface (by pressing the spacebar button) does not reflect the Aha! experience and could not be associated with the translation of egocentric viewpoints into an allocentric reference frame.

In order to isolate the event of interest and its spatial correlates and assess in which cases there is an Aha! effect, the trials are classified into two conditions based on the

expected brain activity. The test condition, that is, the expected brain activity presumably associated with the spatial Aha! moment, includes trials where there was a parietal alpha decrease or a frontocentral theta increase in mean EEG power during 3s before the button-release moment. The isovist properties of the final location of the test condition are compared with the isovist properties of the trials that belong to the control condition. The control condition includes the cases where there was a parietal alpha increase or a frontocentral theta decrease in the mean EEG power during the 3s period of interest.

Comparisons between test and control condition were done: (a) based on the recording of both parietal channels, for the alpha frequency, and both frontocentral, for the theta frequency, (e.g. both channels showed either a decrease or an increase in mean EEG power); and (b) based on the recording of each individual channel of interest, that is the left and right parietal channels (P7 and P8) and left and right frontocentral channels (FC5 and FC6), which includes more trials and permits the investigation of the differences between the two hemispheres. To calculate the relative change in mean EEG power in each condition, the mean EEG total power during the time period of 3s before participants enter the location where they gave their response (3s-0s), is subtracted from an equal length time period before that (6s-3s).

### **3.8 EEG Signal Processing**

#### **3.8.1 Pre-processing**

The EEG data were acquired from 14 channels using the Emotiv headset. The EEG is sampled by the hardware at 2048Hz and then down-sampled to 128Hz (128 data points for one second). The device applies a pass-band filter to the signal to remove frequencies below 0.16Hz and above 85Hz and a notch filter at 50hz and 60hz to remove artifacts produce from the power line.

The pre-processing steps were carried out offline using EEGLAB (Delorme & Makeig, 2004), an open-source toolbox for Matlab (Mathworks, Inc., Natick, MA, USA). To remove slow drift artifacts (in lieu of baseline correction) I have applied a high-pass filter with 1Hz cut-off using the EEGLAB software. The data were cleaned

from artifacts, that were not related to eye-blinks, by manual rejection. An independent component analysis (ICA ‘runica’ function) was then applied to the continuous data (EEGLAB). Stereotyped artifacts such as eye-blinks and eye-movement were detected and removed by the algorithm.

### **3.8.2 Epochs**

The markers for the time-locking events were imported into the data structure of the EEGLAB by custom-written EEGLAB / Matlab scripts. The time-locking events were the button-release moment just before the response, for the response-related analysis, and, for the stimulus-related analysis, the peak change in isovist values within 3s before the button release moment. A different marker was sent for peak values of each isovist property. The information regarding the peak changes in the isovist values and the latency of the events was extracted from a Matlab array, which included data from the movement-related log file and the associated isovist values.

The EEG was then segmented based on these time-locking event. The analysis examines the EEG signal for time-periods of 3s duration, time-locked to the event of interest. However, to avoid edge artifacts resulting from the time-frequency analysis (Cohen, 2014), the epochs were longer in duration than the main time-window of interest (+300ms before the event and +300ms after). For the response-related analysis, data were epoched from -3300ms to +300ms with time references the button-release moment (0s). Stimulus-locked epochs were centred on the peak isovist changes (0s) expanding - 1.8s before and 1.8s after the time-locking event. The control conditions, for both response-locked epochs and stimulus-locked epochs, were epochs of the same duration with an event-marker 3s just before the time-locking event of the test condition. Artifacts were detected using the peak-to-peak function and epochs with deflections exceeding  $\pm 100 \mu\text{V}$  were marked for rejection and excluded from further analysis.

### **3.8.3 Time-domain analysis (ERPs)**

Event-related potentials were examined in relation to the stimulus events of small versus peak changes in the isovist values of revelation, area, clustering coefficient, and visual control. Epochs of the two stimulus-locked conditions were averaged separately for each isovist property, each channel and for each participant. A low-

pass filter with a cut-off at 20 Hz was applied to the epoched data to remove further noise, following the recommendation of the relevant literature (Cohen, 2014, p.97-107).

Even though ERPs are mainly used here as a data quality inspection tool, a basic t-test was run ( $\alpha=0.05$ ) between the two conditions, on the participants' averaged voltage value at each time point. The time-window of significant differences between the conditions was plotted as a grey rectangle to facilitate visual comparison between different conditions and channels. The final plot represents the grand-average of the waveforms across subjects for each condition and each channel.<sup>21</sup>

### 3.8.4 Time-frequency domain

The time-frequency analysis involves techniques that study and represent the signal in both the time and the frequency domain. The Fourier transform is a technique that forms the basis for the representation of the signal in terms of frequency, power, and phase. The Fourier transform computes the dot product between sine waves of different frequencies (the kernels) and the EEG data. (Cohen, 2014, p.121-139). The purpose of the Fourier transform is to find which sine waves with which frequencies, amplitudes, and phases will reconstruct the time series (EEG signal). The reconstruction is done by the inverse Fourier transform (Cohen, 2014, p.121-139). Therefore, by decomposing the time-series EEG data into sinusoid components of different frequencies, we can extract power spectra from a time series. In general, the time-frequency analysis is based on techniques that match the EEG data to a 'template' such a sine wave in the case of the Fourier transform (e.g. Short-time FFT) or a tapered sine wave<sup>22</sup> (e.g. Morlet wavelet convolution) (Cohen, 2017). To extract the power spectra of the EEG data of this thesis I used the second technique (complex Morlet wavelets).

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<sup>21</sup>The signal processing steps for the ERPs were performed in Matlab. A custom Matlab code was written based on material that was provided during the course: Matlab for Cognitive Neuroscience, ICN, UCL Doctoral Skills Development Programme, 2015

<sup>22</sup> A Morlet wavelet looks like a sine wave in the middle but tapers off to zero at both ends (Cohen, 2014, p.143-150).



The type of time-frequency analysis, which is focused on time-locked activity, is called event-related spectral perturbation (ERSP). The relative change in power of a frequency band might be reported as an event-related desynchronisation (ERD) if there is a decrease in power or event-related synchronisation (ERS) if there is an increase. The conversion of raw EEG power to a change in oscillatory power (dB scale) enables comparisons across frequencies, different conditions and subjects (e.g. controls for differences in scalp shape or thickness) since the converted data are now in the same scale.

The time-frequency decomposition was performed in Matlab and I wrote the codes for the wavelet transformation having as a guideline Cohen's book, "*Analyzing neural time series data: theory and practice*" and the associated scripts (Cohen, 2014). The oscillatory power was obtained by convolving the EEG signal with wavelet cycles (4-10 cycles) that varied as a function of frequency. Power values were obtained for 40 logarithmically spaced frequency bands in the 2–30 Hz range. The time-frequency analysis was done using a complex Morlet wavelet transformation on every single trial, rather than the participants' average and the power values were log-transformed (ibid.) Time-frequency data were extracted for epochs that were longer in duration than the time-window of interest. These extra 300ms before and after the 3s period of interest were discarded after the convolution to avoid edge artifacts.

For the response related analysis, the oscillatory power values were averaged over the time period of the control condition (-6s to -3s) and frequency windows of 4-7Hz and 8-12Hz and subtracted from the average oscillatory power, over time (-3s to 0s) and over the same frequency windows, of the test condition (0s - button-release). These differences in power spectral between the two response-related time-windows were used to classify trials into test (alpha ERD / theta ERS) and control conditions (alpha ERS/theta ERD). The oscillatory power values, for the stimulus-related analysis, were averaged over the time period of the control condition (-4.5s to -1.5s) and frequency windows of interest (2-8Hz) and subtracted from the average oscillatory power of the time window of -1.5s to 1.5s and over the same frequency window, of the test condition (0s - peak change in isovist value).

### Single-trial analysis

The traditional approach to time-frequency analysis and time-domain analysis is to demonstrate differences between the average of trials across groups of subjects or conditions. For example, the spectral decomposition of the data is usually applied on trial-average of each subject rather than single trials. The averaging of trials that belong to similar experimental conditions increases the signal-to-noise ratio, and the variance that is randomly distributed averages out (Cohen & Cavanagh, 2011). However, in some experimental cases, variance across trials might be related to the hypothesis of the study and thus it may contain information about cognitive states (Pernet et al, 2011). In these cases, behavioural and experimental variables and thus brain dynamics may vary from trial to trial. These cases include studies that investigate neural dynamics in relation to response time, decision making, stimulus information or visual stimulus parameters (ibid.).

Thus, single-trial analysis has several advantages over group analysis especially in experimental condition that consider the variance within subjects. In this paradigm, the amount and distribution of visual information vary from trial to trial. Additionally, participants may release the movement button for reasons that are not related to recollection or familiarity. For example, they might decide to stop and press the spacebar response-button to just check the map. Therefore, the variance within subjects is considered and examined, by adopting a single-trial approach to the time-frequency decomposition of the signal.

### 3.9 Statistical Analysis

Analyses of the collected data were focused on the within-subject factors because the same participants provided data points for all conditions analysed. Data were analysed using the IBM SPSS software (IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.) P-values  $<0.05$  were considered statistically significant. The error bars of all bar plots and of raincloud plots display standard errors of the mean (S.E.M.). Raincloud plots (Micah et al, 2019) illustrate data points of the averaged values for each participant, their distribution and the mean of these data points. A detailed statistical analysis is described below. The last part of the

section provides a brief description of the main statistical tests that were used (i.e. parametric tests, non-parametric tests, and binary logistic regression analysis).

The Shapiro-Wilk test of normality was used to assess the normality of the data set since normal distribution of the data is a prerequisite condition for the use of any parametric statistical test e.g. ANOVA. Statistical analyses of a) the peak isovist values during different time-periods<sup>23</sup> and b) the isovist values at the button-release location (for ‘test’ versus ‘control’ response-related conditions of brain dynamics) were performed using repeated measures ANOVA (General Linear Model). A one-way repeated measures ANOVA was used to compared peak isovist values between the different time-periods. In this case, the assumption of sphericity<sup>24</sup> was not met (Mauchly's test of sphericity,  $p\text{-value} < 0.05$ ) and, therefore, the Greenhouse- Geisser corrected values were used to report the results. A two-way repeated measures ANOVA with levels of channel and condition was used to analyse the isovist values at the button-release location (parietal alpha decrease versus alpha increase and frontocentral theta increase versus decrease). Post-hoc t-tests with Bonferroni correction for multiple comparisons were performed when a significant effect was found.

In cases when the data were not non-normally distributed (Shapiro-Wilk test  $p\text{-value} < 0.05$ ), a Friedman's test was used to compare repeated-measures. Data were not normality distributed in the following cases: a) the isovist values of revelation at the button-release location, which were compared between test and control response-related conditions of brain dynamics and b) the data sets of the stimulus-related change in EEG power, which were compared between the two conditions of environmental change (small versus large peak changes in isovist values) for all isovist properties. Follow-up non-parametric Wilcoxon's signed rank tests with Bonferroni correction for multiple comparisons were performed where appropriate.

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<sup>23</sup> and at the four distance-segments as well

<sup>24</sup> That means that there are significant differences between the variances of all possible differences between the values of the different time-periods

Additionally, a one-way repeated measures ANOVA was used to examine the differences in the mean angular error of each participant's response between the different confidence rating categories (with post-hoc pairwise comparisons using Bonferroni correction). And, a non-parametric Friedman test was performed to compare a) the percentage of correct responses and b) the percentage of responses with high confidence rating between the three urban environments. In these cases, the data sets were not normally distributed (Shapiro-Wilk test  $p\text{-value} < 0.05$ ). The Pearson correlation coefficient was used to assess the relationship between pairs of continuous variables such as the ratio of correct response to total responses in relation to individual differences (i.e. age and spatial abilities' SBSOD score).

Also, a binary logistic regression analysis was employed to examine the predictive strength of spatial (and non-spatial variables) with respect to the probability of the occurrence of the response-related brain activity. In other words, it was used to assess whether the single-trial isovist values at the button-release location could predict the probability of the occurrence of a parietal alpha decrease, and of a frontocentral theta increase during the 3s period before the button-release. The binary logistic regression model describes the relationship between the spatial predictor variable and the response (expected brain dynamics). The analysis initially included only the isovist properties that were found, by the two-way repeated measures ANOVA, to be significantly different between these two conditions. To further study this relation, I also included in the model non-spatial factors, such as the age (for the parietal alpha brain response) and the SBSOD score (for the frontocentral theta response).

### **Repeated measures ANOVA**

The one-way repeated measures ANOVA is used to compare the means of three or more groups. These groups consist of multiple measures of the same variable under different conditions or time-periods and all subjects provide a data point in each group. The null hypothesis is that all group means are equal. The two-way repeated measures ANOVA compares the means in the different groups across two independent variables (e.g. time-periods and conditions) as well as the interaction between them, and again the same participants provide data points for all the cases.

The ANOVA calculates the F-ratio which is a measure of the ratio of the systematic variance and the unsystematic variance (Field, 2013). In other words, it is the ratio of the size of the variation due to the experimental manipulation to the size of the variation due to factors that are random such as individual differences in performance (ibid.). If the F-ratio is large enough to be significant then there is a significant effect, and this tells us that the means of two or more conditions are significantly different. However, to identify which are these cases, we need to run post-hoc tests (pairwise comparisons) using a Bonferroni correction. The Bonferroni correction is an adjustment of the alpha value (0.05). This correction is necessary because when performing multiple t-test on the same data, the chance of getting a Type I error increases. Type I error describes the cases where we have statistically significant differences ( $p \text{ value} < 0.05$ ) when there is actually no effect. If alpha is 0.05 then the probability of this error, for one t-test, when there is no effect on the population, is 0.05 (or 5%) but as the number of t-test increases, this percentage increases as well (Field, 2013). Therefore, the easiest way to control for this error is to divide the alpha by the number of comparisons (or multiply the p-value of each t-test by the number of comparisons).

However, several assumptions need to be met in order to use the ANOVA. The distribution of the data within groups should follow an approximately normal distribution, otherwise, a non-parametric test should be used instead. The assumption of normality can be tested using the Shapiro-Wilk test of normality. In addition, the dependent variable needs to be continuous and the variances of the differences between conditions should be roughly equal (assumption of sphericity). The assumption of sphericity can be tested using the Mauchly's test, and if the significance of this test is less than 0.05 then that means that the assumption of sphericity has been violated. In these cases, the Greenhouse and Geisser and Huynh and Feldt corrections procedures "give rise to a correction factor that is applied to the degrees of freedom used to assess the observed F-ratio" (Field, 2013).

### **Non-parametric tests**

Non-parametric tests do not require a normal distribution of the data and thus provide an alternative option to ANOVA when this assumption is not met. The

Wilcoxon's signed-rank test can be used for comparison between two related groups and the Friedman's test for comparison between more than two related groups. Both tests are based on ranked data. The main logic here is that if the conditions that are compared have a similar number of high and low ranks, then adding up these ranks will result in similar outcomes (Field, 2013).

For the Wilcoxon's signed-rank test (Field, 2013, p. 552-558), the differences between the two groups are calculated and then they are ranked (e.g. lower score has a rank of 1, the next higher a rank of 2, and so on) with a positive or negative sign depending on the direction of the difference. In other words, large positive or negative ranks represent large differences. Then, the sum of all positive ranks and the sum of all negative ranks are calculated. To calculate the significance of the test statistic (if  $p < 0.05$ ), the lowest of these two values is converted to a z-score (for more details on the equation see Field, 2013, p.553-554).

The Friedman's test (Field, 2013, p.573-583) is used when several conditions are compared, and participants provide a data point for each condition. In this case, the ranking is based on the score of each participant in each condition. That is, the lowest value for each participant gets a rank of 1. After ranking the data points of each participant, the sum of the ranks for each condition is calculated. The square of the sum of ranks of each condition, the sample size and the number of conditions are used to calculate the test statistics,  $F$ , which has a chi-square distribution (for more details on the equation see Field, 2013, p.574). If the overall effect is found to be significant, then follow-up test can be performed using, for example, non-parametric Wilcoxon signed-rank tests with a Bonferroni correction.

### **Binary logistic Regression**

The binary logistic regression (Field, 2013, p.264-313) is a method of statistical testing that permits the calculation of the probability of the event of interest ( $Y$ ) occurring (success vs. failure) for given values of the independent variables ( $X$ s). It is used in cases where the outcome or response variable is categorical in contrast with linear regression where the response variable is continuous. Applying a logarithmic transformation to the data permits to express this relation in a linear way,

although the response is binary. This method, therefore, uses natural logarithm to produce a logistic curve. In this way, the model expresses the equation of multiple regression but in logarithmic terms (logit) (Field, 2013, p.266):

$$P(Y) = \frac{1}{1 + e^{-(b_0 + b_1 X_{1i} + \dots + b_n X_{ni})}}$$

where  $e$  is the base of the natural logarithms,  $b_0$  is the constant and  $b_n$  the coefficient of predictor  $X_n$  and  $P(Y)$  the probability of the occurrence of the event  $Y$ .

We can assess whether the model is a good fit for the data by looking at the deviance ( $-2 \times \log\text{-likelihood}$ ) and the difference between the deviance of different models. It is usually used to assess whether the model improves or not by adding an explanatory variable to the null/ baseline model where only the constant is included. This difference is called a log-likelihood and has a chi-square distribution with degrees of freedom (df) equal to the number of parameters added to the model. Also, Hosmer & Lemeshow's  $R^2$  and Nagelkerke  $R^2$  can be used to measure the effect size of the model. They describe the proportion of variance in the outcome that the model explains. The Hosmer & Lemeshow statistics test whether the predicted values are significantly different from the observed and a nonsignificant value ( $p > 0.05$ ) indicates that the model fits the data well (Field, 2013)

For the interpretation of the contribution of each predictor, we look at the value of the  $b$  coefficients which are the values that are entered into the equation to calculate the probability that a trial falls within a certain category. Also, the Walds statistics (analogous to the t-test) show whether the predictor makes a significant contribution to the prediction of the outcome (as indicated by the p-value). The  $b$  coefficient is used to calculate the odds ratio. The odds ratio is the exponential of  $b$  ( $\exp(b)$ ) and indicates the change in odds that results from a unit change in the predictor if the predictor is continuous. If the predictor is categorical, then the odds ratio reflects how many times is more ( $\exp(b) > 1$ ) or less ( $\exp(b) < 1$ ) likely for the event to occur for category  $X$  in comparison to the baseline/reference category.

To clarify, “the odds of an event occurring are defined as the probability of an event occurring divided by the probability of that event not occurring” (p767).<sup>25</sup> The proportional change in odds of two cases (either categories or one change in unit) is the odds ratio. The threshold at which the direction of the effect changes is value 1. The 95% confidence intervals give a sense of sampling error associated with the odds ratio. If the confidence intervals contain 1 or are close to 1 that means that factor is considered to be statistically non-significant. This is because it suggests that within the range of values that would contain the true parameter 95% of the times, some values might suggest that the variable improves the probability of the event Y to occur, but equally it might be a value that suggests that the variable decreases the probability of the event occurring (ibid).

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<sup>25</sup> Number 1 describes equal odds, that is one success trial for every one failure while equal probabilities are 0.5, which describes one success in every two trials.



## **CHAPTER 4      Analyses of Spatial Behaviour and Brain Dynamics**

## 4.1 Introduction

This first part of the data analysis examines participants' spatial behaviour. Their performance shows that they were able to perform the task and were engaged with the task during the experiment. The effect of several navigation relevant factors on participants' accuracy, such as age, professional background, gender and individual differences in spatial abilities, is also explored. The heading bearing from the North at the response location is an important factor as well. This is because spatial representations are viewpoint-dependent and, according to Meilinger (2008), the information is encoded in an allocentric frame of reference with North<sup>26</sup> (up) as a reference direction when studying a map of a spatial configuration. Therefore, the angular offset between heading direction at response locations and North (i.e. the orientation at which the map was presented during the study phase) was expected to affect performance (e.g. angular error) in each trial. Participants' response accuracy, however, is more related to the successful heading retrieval aspect of the re-orientation process which is not the central issue, because the thesis focuses on the sub-process of context recognition. Therefore, the factor of accuracy is not explored further.

Participants' exploratory behaviour shows their patterns of movement and pauses in relation to the spatial layout. Isovist values of the relevant properties are examined along a single participant's paths to visualize their relation to the button-release moment. This is done in relation to both the time and distance travelled. The mean peak values of the isovist properties are initially compared across four different time-intervals of 3s duration and four different distance-segments of 15m length before participants' button-release response. The distance-related analysis is done here in order to ascertain that any significant differences in isovist values between the time-periods are not produced by variations in speed or in stationary behaviour.

To clarify which of the two hypotheses is better supported, the behavioural analysis investigates where it is more likely for participants to stop their movement in order to give their response and if there is a significant sudden increase or decrease (in the

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<sup>26</sup> since maps are usually experienced in that orientation

case of clustering coefficient) in the isovist measures just before this moment. The frequency distribution of isovist values at button-release location illustrates where it is more likely for participants to give a response and a comparison of two of the time-windows preceding the button-release moment (0s-3s and 3s-6s) reveals the differences in isovist peak values.

The second part of this chapter examines the relationship between participants' brain dynamics and the relevant isovist properties. There are two events of interest that drive this part of the analysis: (1) moments when the visuospatial information changes suddenly in the time preceding the button-release (up to 3s) just before the response; and (2) the moment when participants' release the movement button to respond to the task, as they believe they have oriented themselves.

The stimulus-related analysis examines brain activity in relation to two spatial conditions: peak changes in isovist values (during the time period of interest) that fall (a) below; and (b) above the median change in value for each isovist measure. The EEG signal, time-locked to this event, is examined in the time-domain and time-frequency domain. The event-related potentials (ERPs) show several differences between the two conditions, which are more pronounced in the waveforms of the frontocentral electrodes. The focus of the time-frequency analysis is on the EEG power over frontocentral channels at the frequency range of 2Hz to 8 Hz because, according to the literature, theta oscillations related to periods of movement typically occur at a lower frequency during virtual navigation, peaking around 3.3Hz (Bohbot et al, 2017; Jacobs, 2014). Frontocentral delta increase was associated with stimulus evaluation (Yordanova et al, 2000) and complex stimulus processing (Bachman & Bernat, 2018). Frontocentral theta increase has been associated with spatial working memory demands (Jaiswal et al, 2010; Lin et al, 2015). Thus, the processing of visuospatial information that is significant for navigation should be reflected by increases in frontocentral delta/theta activity.

The brain dynamics that are associated with the moment of spatial re-orientation (the Aha! effect) are examined in relation to the moment that participants release the movement button and enter the location where they give their response. Literature on the brain's response to deviant/task-related events on navigation, orientation and on

insightful problem solving suggest that the Aha! experience of spatial re-orientation might be related to a specific pattern of brain activity: a posterior alpha decrease in power and a more frontal increase activity in the theta band. To assess and compare the conditions that are most likely accompanied by an Aha! experience to those that are not, trials are classified into two groups based on the alpha-related and theta-related differences in EEG power.

However, besides spatial geometric factors, other factors such as individual differences or the presence/absence of landmarks may influence the processes related to the spatial re-orientation. The third section of this chapter examines the role of these non-geometric factors. The presence of landmarks is investigated in relation to participants' performance and their brain dynamics. According to the literature, the presence of target-buildings, during a taxi-driver navigation game, resulted in a decrease in theta activity at the right anterior inferior region of the brain, which includes the channel FC6 (Weidemann et al, 2009), and navigation in landmark-enriched environments was associated with a decrease in theta power at the left hemisphere (parietal cortex) (Sharma et al, 2017). However, no such differences were found at these electrodes between trials where a landmark was seen during a time-period of 3s before the response and in trials where no landmark was seen.

To examine the influence of individual difference on spatial re-orientation I have looked at other factors that may influence the parietal alpha power decrease and the frontocentral theta increase. Age is a factor that affects navigation skills, as well as context updating processes (representational change) since studies on the P3 component, provide evidence that the amplitude of the component is reduced for older vs. younger adults (Polich, 2012). Thus, a binary logistic regression model examines the role of age as an additional independent variable in predicting the parietal alpha decrease. The frontocentral theta response, as mentioned in section 2.2.4, might reflect the allocation of attentional resources for the evaluation of the available choices for movement and/or recognition-related decision making. It is not unreasonable to think that if one has difficulties in evaluating the available environmental information, then this will influence decision making. This will most likely result in an increase in theta power reflecting increased spatial processing and attentional load. The Santa Barbara Sense of Direction test (SBSD), a subjective

assessment of the sense of direction, indicates how confident one is with their ability to orient in space and to respond to the experimental tasks. This suggests that people who score low at this test will most probably have difficulties in evaluating the visuospatial information which might be reflected in differences in the theta power. Therefore, a binary regression model examines this variable (SBSD) in relation to the frontocentral theta increase.

## 4.2 Spatial and Behavioural Analyses

### 4.2.1 Performance

Participants could perform the task with ease and be engaged during the whole procedure. The total number of responses that were included in the analysis was 465 (Table 4.2-1). Mean number of trials per participant was 23.3 (min=20 trials, max=24). Variation in the number of trials is due to problems that emerged with the game engine during testing. Mean performance across participants was 61.7% (SEM=5.25%) of correct responses, which was significantly greater than the chance level of 16.67% [ $t(19) = 8.68$ ;  $p < 0.001$ ].

Response	Total	Correct	Incorrect	Confidence Rate 3 <i>Certain</i>	Confidence Rate 2 <i>Probably right</i>	Confidence Rate 1 <i>Uncertain</i>	No final Response
City 1	158	80	44	51	37	36	34
City 2	154	104	34	79	37	22	16
City 3	153	103	34	77	34	26	16
Total	465	287	112	207	108	84	66

Table 4.2-1. Number of responses per category of accuracy and confidence rating

Participants' confidence ratings were generally high (mean=2.31, SEM=0.04). This shows that in most trials, participants felt certainty about their position in space and they perceived their response as accurate. Moreover, a paired-samples t-test was conducted to compare the average confidence ratings of each participant for correct and non-correct responses (incorrect and no-final-response). There was a significant difference [ $t(19) = 8.82$ ;  $p < 0.001$ ] in confidence ratings across participants between correct (mean=2.47; SEM=0.09) and non-correct responses (mean=1.68; SEM=0.11). Similarly, as shown in Figure 4.2-1, mean angular error across participants in trials with high confidence ratings (Confidence Rat. = 3, 'certain'), was below 30 degrees (mean=20.96 degrees, SEM=4.65). The 1x3 repeated measures ANOVA

found a significant difference in the mean angular error of each participant between the different confidence rating categories [ $F(13)=14.20$ ,  $p<0.001$ ]. Post-hoc pairwise comparisons using Bonferroni correction revealed that trials where participants reported a confidence rating 3 had a significantly lower angular error than trials with confidence rating 2 ( $p=0.045$ ) and 1 ( $p<0.001$ ). Mean angular error between trials with confidence rating 2 and 1 did not differ significantly ( $p=0.067$ ).

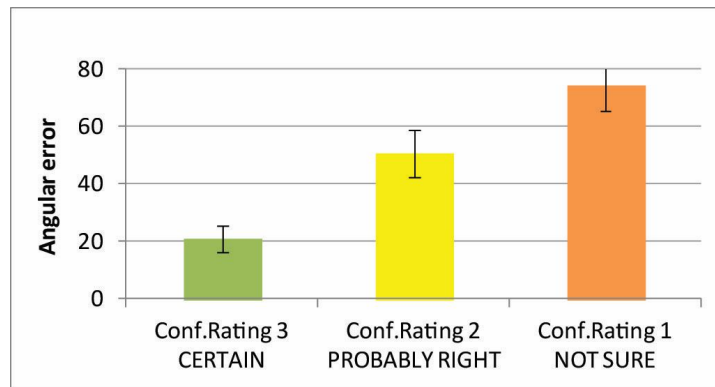


Figure 4.2-1. Mean angular error of responses across participants for the three levels of confidence ratings. 3 (certain), 2 (probably right) and 1 (uncertain).

Participants' performance (accuracy and certainty of response) was compared between the three virtual cities using a non-parametric Friedman test<sup>27</sup>. There were no significant differences in the percentage of correct responses between the three cities [ $\chi^2(2) = 5.507$ ,  $p = 0.064$ ]. However, there was a significant difference in the percentage of responses with high confidence rating (certain) between the three cities [ $\chi^2(2) = 7.507$ ,  $p = 0.023$ ]. Dunn-Bonferroni post hoc tests were carried out and there were significant differences only between city 1 (mean=0.44, SEM=0.074) and city 2 (mean=0.57, SEM=0.069).

Additionally, participants' performance might be influenced by individual differences such as age, gender, professional background or spatial abilities as well as factors that are related with each individual's route such as path length or heading direction at the button-release location (Table 4.2-2). To examine their possible effect, I looked at the relationship between these factors and participant's performance using an independent t-test. Participants with a professional background related to the built

<sup>27</sup> The assumption of normality for the repeated measures ANOVA was violated.

environment ( $N=10$ , mean=62%, SEM=0.06) did not perform significantly better [ $t(18)=0.13$ ;  $p=0.90$ ] than the other participants ( $N=10$ , mean=61%, SEM=0.09), nor was there a significant difference [ $t(18)=1.04$ ;  $p=0.31$ ] in performance between male ( $N=11$ , mean=66%, SEM=0.07) and female participants ( $N=9$ , mean=56%, SEM=0.07). In addition, no correlation was observed between participants' performance and age (Pearson's  $R=0.273$ ;  $p=0.24$ ). Similarly, the Santa Barbara Sense of Direction score (SBSOD), which is a self-report measure for spatial abilities (Hegarty et al, 2002), shows no correlation with participants' performance (Pearson's  $R=-0.076$ ;  $p=0.75$ ).

	Min	Max	Mean	SEM
Correct/Total	14%	92%	62%	0.05
Angular Error (degrees)	7.29	76.06	34.72	4.6
Confidence Rating	1.53	2.88	2.3	0.09
Gender-Female ( $N=9$ )	25%	86%	55%	0.07
Gender-Male ( $N=11$ )	15%	92%	66%	0.07
Professional Practice- Related discipline ( $N=10$ )	15%	86%	62%	0.06
Professional Practice- Non-related discipline	25%	92%	60%	0.09
Age (years)	20	43	33.75	1.12
Santa Barbara Sense of Direction (out of 7)	3.33	6.47	4.7	0.23
Trial Duration until response (seconds)	13.25	314.52	97.88	8
Distance travelled until response (virtual meter)	26.83	2446.54	475.27	33.88
Heading Directional at response (degrees)	0.1	179.08	92.02	2.24

Table 4.2-2. Descriptive statistics of navigation relevant factors.

Distance travelled within each route and the duration of each trial might indicate the amount of spatial information that an individual was able to acquire during each trial. Mean trial duration across participants (from the start of the trial until first response) was 98s, and the mean distance travelled was 475 virtual meters. There was no significant difference in distance travelled [ $t(19)=-0.08$ ;  $p=0.94$ ] between trials with correct (mean=478.25, SEM=38.92) and incorrect responses (mean=483.84, SEM=66.65) nor was there any significant difference [ $t(19)=-0.89$ ;  $p=0.39$ ] in trial duration between trials with correct (mean=95.50 sec, SEM=8.31) and incorrect responses (mean=105.74 sec, SEM=14.22).

Finally, according to the literature spatial representations are more easily accessible if the current view is aligned with the initial viewpoint during learning, which in this case is the orientation of the map (North). Thus, another factor that seems to

influence heading retrieval, and thus participants' angular errors in the task, is the heading bearing from North at the button-release location. A paired t-test revealed that the angular offset between heading direction at these locations and North (Figure 4.2-2) was significantly greater for Incorrect (mean=102 degrees, SEM=5.38), compared to Correct responses [mean=87 degrees, SEM=3.3;  $t(19)=2.13$ ;  $p<0.05$ ].

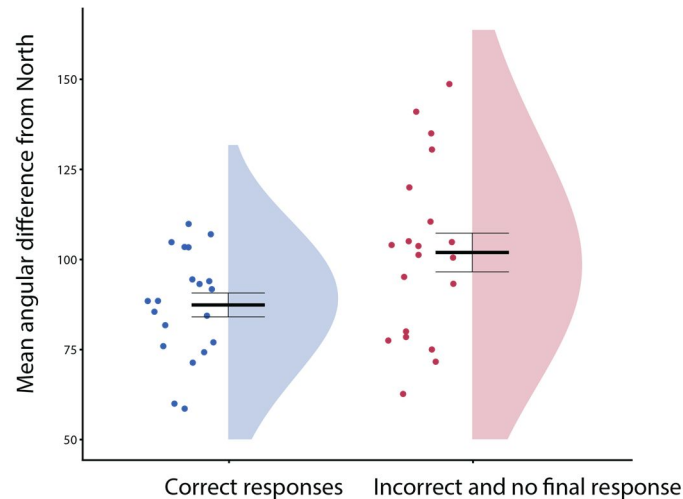


Figure 4.2-2. Heading direction in relation to North at the button-release location.

#### 4.2.2 Exploratory behaviour

Each participant's path in each trial (from the origin location to the final button-release location) is shown against the spatial layout of each virtual city in Figure 4.2-3. This illustration allows us to draw some initial inferences regarding participants exploratory behaviour and responses. Several routes seem to overlap since the eight starting locations were the same for all participants. Although participants do not seem to choose the same trajectory of movement when starting their exploration from the same location, visual inspection suggests that participants tend to move towards streets with long lines of sight. Button presses locations (Figure 4.2-4), as well as pauses (Figure 4.2-5), do not happen at random locations but they appear to cluster around junctions, urban squares, and landmarks. To assess which spatial properties drive the spatial re-orientation, and which of the two hypotheses is better supported by the data, further analysis is focused on the relevant isovist properties and their relation to the button-release moment just before their response to the task.



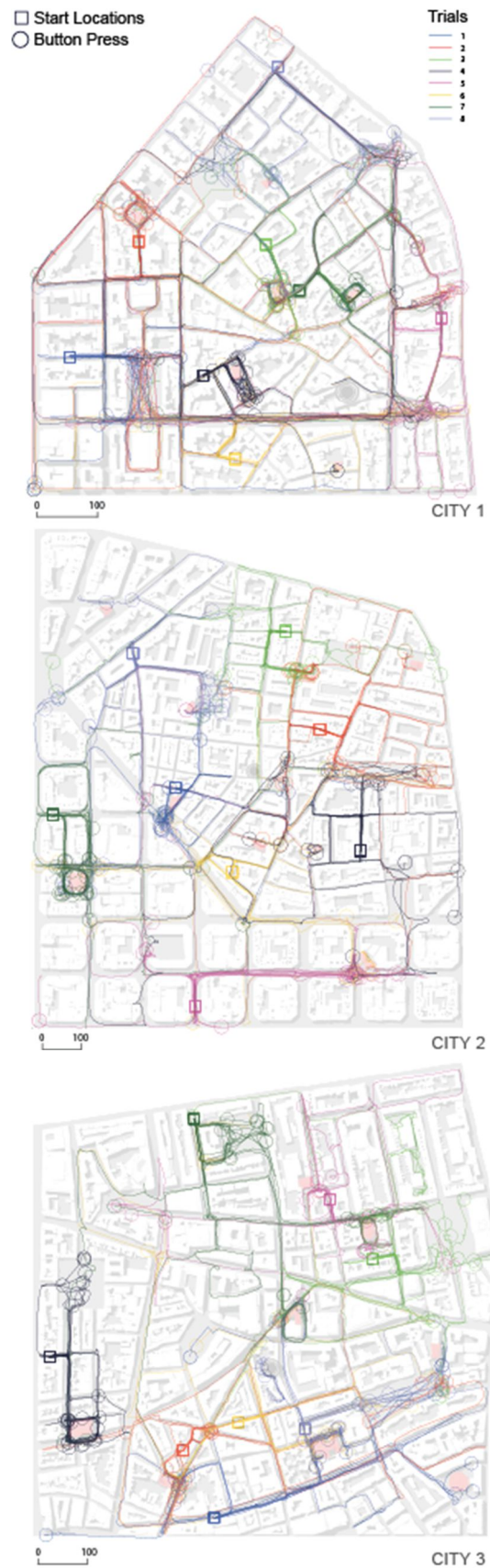


Figure 4.2-3. Exploratory behaviour of participants. The paths from each starting point are illustrated in different colours. The order of each trial was different for every participant.



Figure 4.2-4. Button presses in relation to urban squares and landmarks

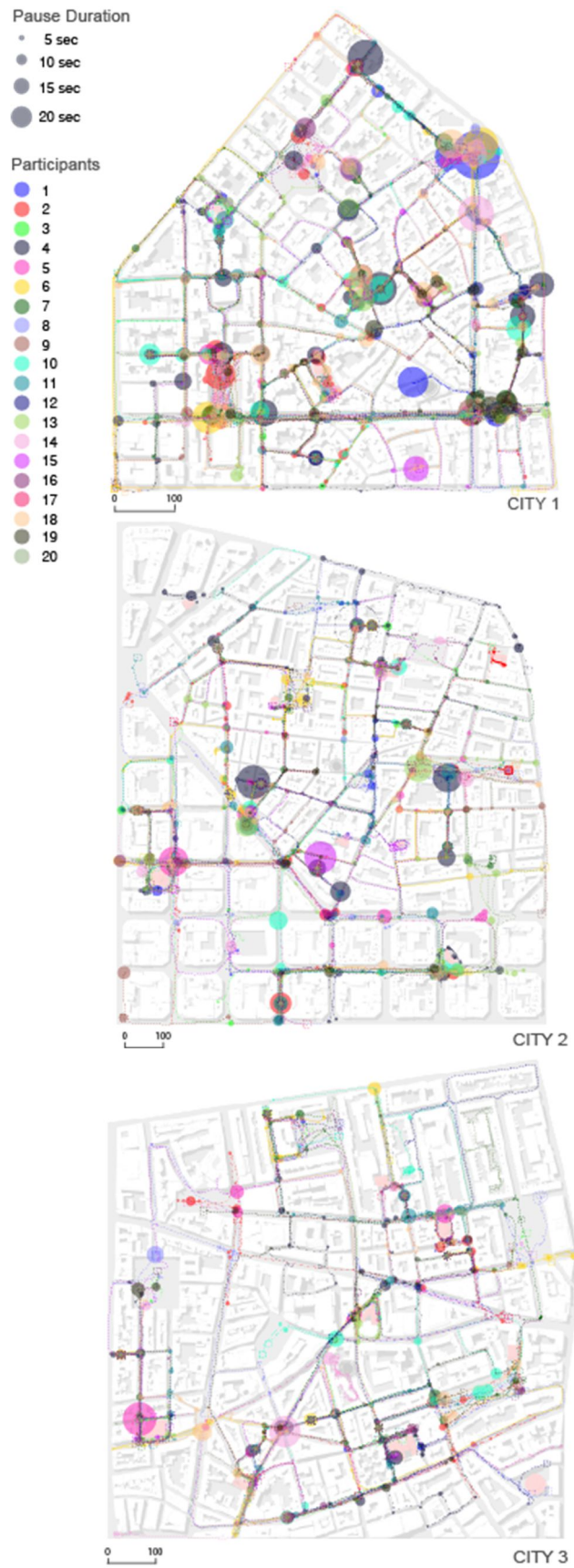


Figure 4.2-5. Location and duration of pauses during exploration.

### Visibility graph analysis and isovist paths

The three environments do not have great differences in terms of the distribution of the isovist values, as shown in Table 4.2-3, except in the case of city two, where the region with the orthogonal grid has locations with much higher values of revelation and area, compared to the other virtual urban environments. As discussed in detail in section 2.3.3, the isovist properties of revelation and area are associated with the factor of ‘spaciousness’ and can describe the change in the amount of visual information, whereas clustering coefficient and visual control capture the change in the complexity of the visual information. Figure 4.2-6 and Figure 4.2-7 represent graphically the results from the visibility graph analysis (VGA) and the distribution of the values of the isovist properties that correspond to the two hypotheses: revelation and area, clustering coefficient and visual control respectively.

ISOVIST PROPERTIES		Mean	Standard Error of Mean	Median	Standard Deviation	Min	Max
<b>City 1</b>	<i>Area</i>	5043	36	3355	4441	48	23155
	<i>Revelation</i>	452	6.51	161	793	0.38	8944
	<i>Clustering Coefficient</i>	0.82	0.00	0.86	0.14	0.32	1.00
	<i>Visual Control</i>	1.00	0.00	0.96	0.33	0.04	2.64
<b>City 2</b>	<i>Area</i>	13826	52	10928	10859	161	61730
	<i>Revelation</i>	939	7.75	291	1627	0.02	17058
	<i>Clustering Coefficient</i>	0.80	0.00	0.84	0.14	0.30	1.00
	<i>Visual Control</i>	1.00	0.00	0.95	0.35	0.07	2.89
<b>City 3</b>	<i>Area</i>	7547	28	6809	5036	104	26898
	<i>Revelation</i>	552	4.42	254	799	0.04	8598
	<i>Clustering Coefficient</i>	0.79	0.00	0.83	0.15	0.24	1.00
	<i>Visual Control</i>	1.00	0.00	0.94	0.33	0.06	3.25

Table 4.2-3. Descriptive statistics of isovist properties of each virtual city



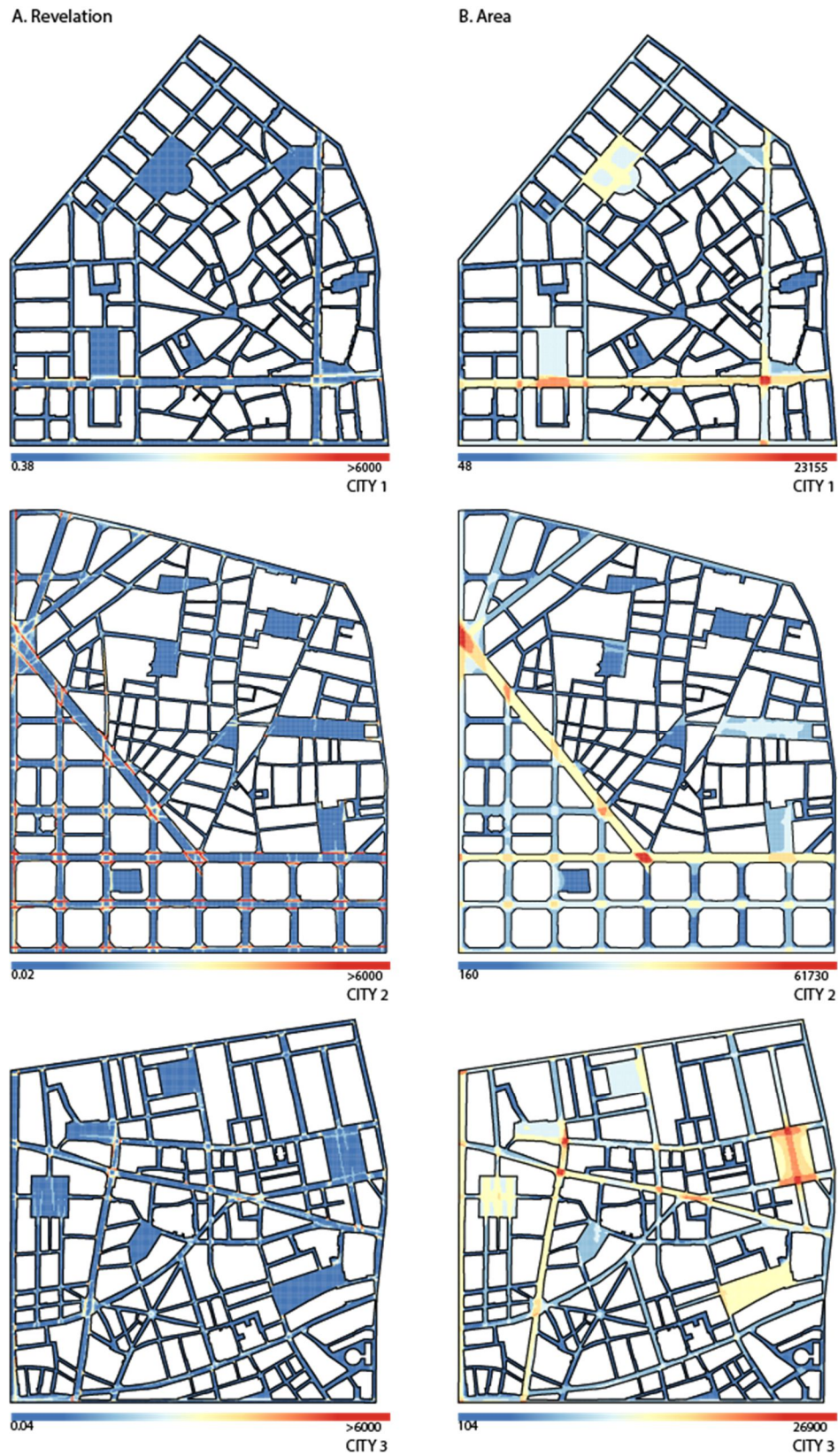


Figure 4.2-6. Visibility graph analysis for the three virtual environments (Hspaciousness) (A) isovist revelation and (B) isovist area

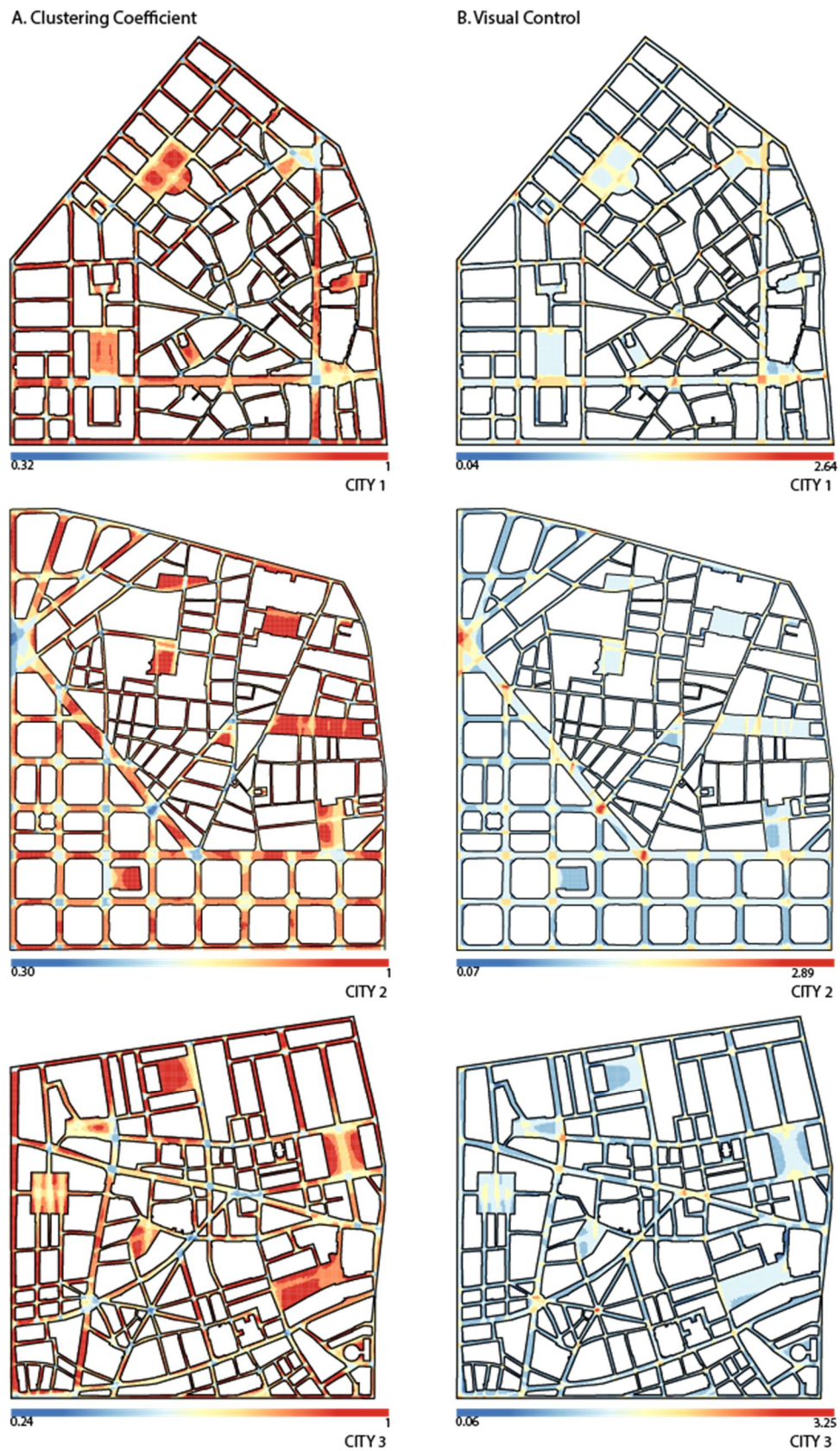


Figure 4.2-7 Visibility graph analysis for the three virtual environments (Hcomplexity) (A) isovist clustering coefficient and (B) isovist visual control



Isovist paths offer a graphical representation of the changes that an individual can perceive in each route. The isovist path charts show the value of each property (vertical axis) at distinct point locations along each path (horizontal axis). To illustrate this relation between the individual and the environment, that is the 'visual rhythm' of the participant's path just before the button-release moment, I have focused on the trials of one participant in one city environment (Figure 4.2-8).

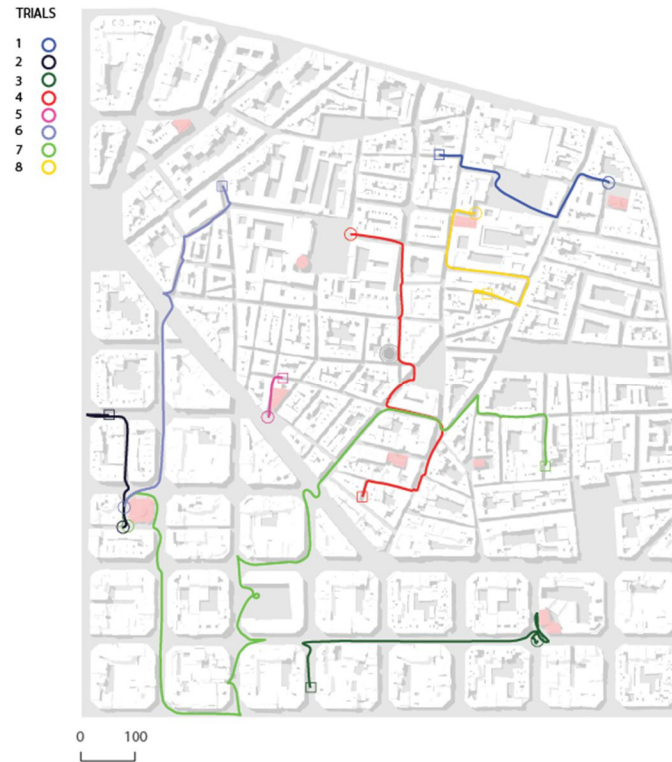


Figure 4.2-8. Exploratory behaviour of a participant from each of the 8 starting locations.

The isovist values are unfolded along each path both in relation to time (Figure 4.2-9) and in relation to distance (Figure 4.2-10). Both figures show the changes in the values of isovist properties along the route just before the button-release moment. These isovist paths show that in most cases there is '*crescendo effect*', 3s before the response, in the measure of visual control and in fewer cases in area and revelation. In the plots of the clustering coefficient, the values drop in most cases, just before the button-release response. Another interesting point is that isovist paths show that the environmental input varies in each trial, which might result in variability in neural responses. Therefore, averaging trials to analyse the brain dynamics of each participant, which is the traditional approach, may not be the most appropriate option here.

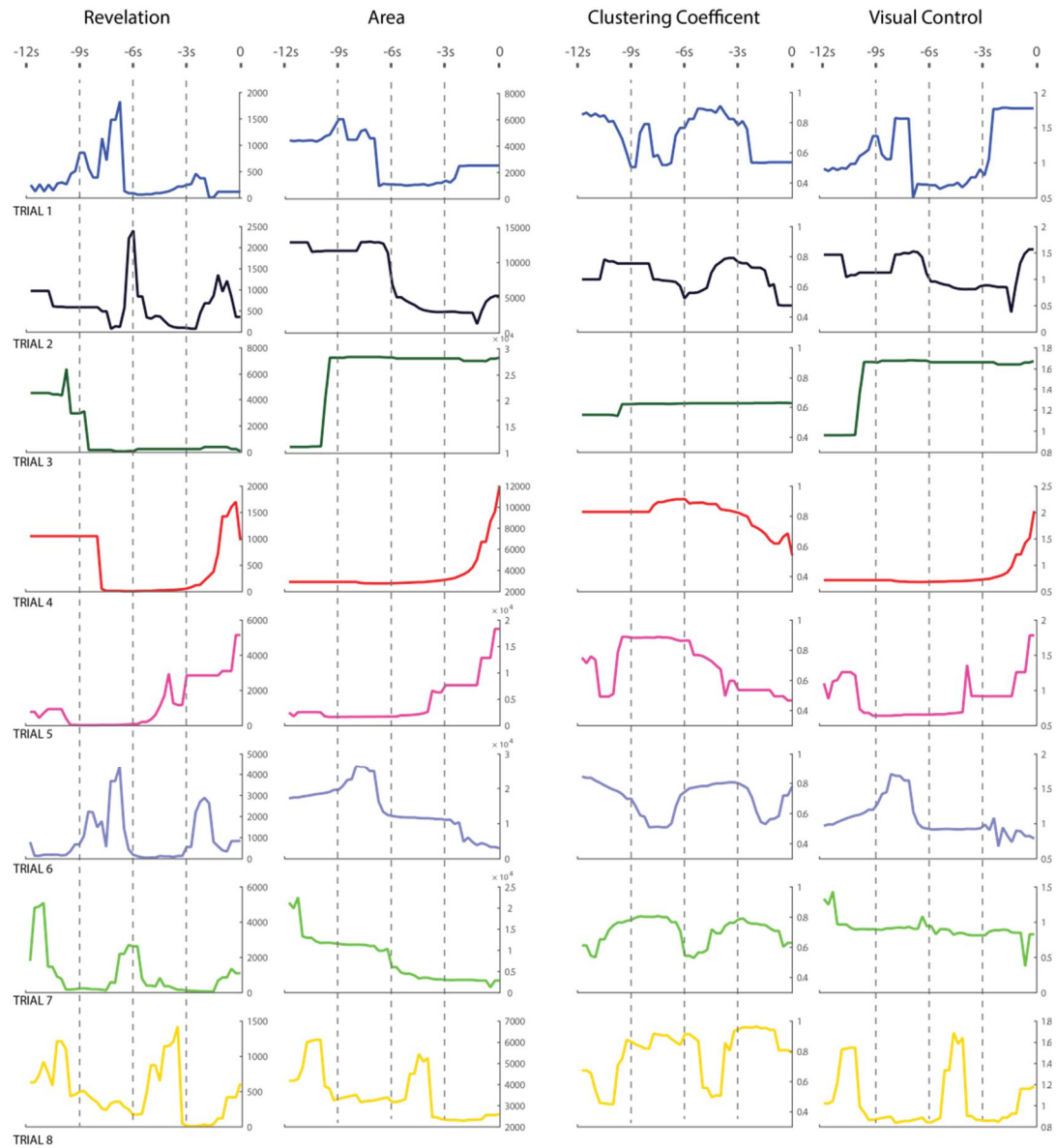


Figure 4.2-9. Isovist paths for revelation, area, clustering coefficient and visual control in relation to time. The isovist values are unfolded along participant's path for each trial (1-8) in virtual environment 2.

The same pattern can be also observed when the isovist values are unfolded in relation to distance rather than time (Figure 4.2-10). The changes in isovist values of revelation, area, clustering coefficient, and visual control are plotted in a similar manner as in Figure 4.2-9 to facilitate the visual comparison. They are visually divided into four successive chunks of 15m since participants' mean distance travelled during the 3s time period of interest is 14.92 virtual meters (SEM=0.50).



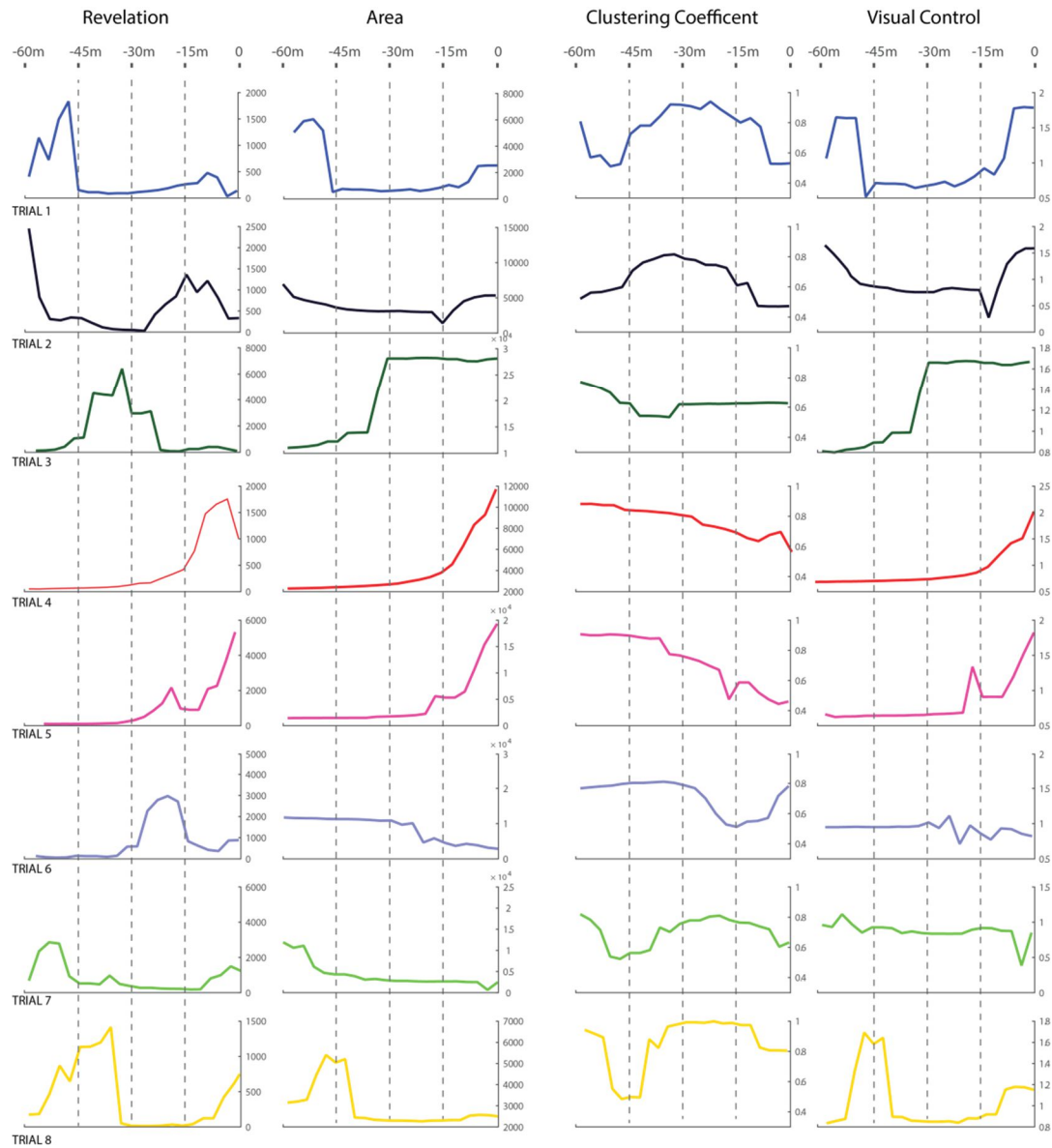


Figure 4.2-10. Isovist paths for revelation, area, clustering coefficient and visual control in relation to distance. The isovist values are unfolded along participant's path for each trial (1-8) in virtual environment 2.

#### 4.2.3 Isovist properties driving spatial re-orientation

The isovist paths figures (Figure 4.2-9, Figure 4.2-10) illustrate how the measures of interest often reach peak values (in relation to the rest of the route) just before participants decision to release the movement-button in order to stop and give their response to the task at this final response-location. To examine which set of isovist properties drive the moment of spatial re-orientation, the values of revelation, area, visual control, and clustering coefficient are compared for different time periods of equal duration (3s) that precede the button-release moment. To ascertain that the

results of the analysis are not the product of variations in distance travelled, a similar comparison is done for distance segments of equal length (15m) before the response. If the null hypothesis is true, then the mean values of each isovist property will be constant between these time windows. Alternatively, if changes in any specific isovist property contribute to the moment of spatial orientation, this should manifest as a significant difference in the mean value of that property between the two time-windows closer to the response, that is of the time periods of 6s-3s and 3s-0s. Therefore, the hypotheses for the research question “*Which spatial metrics might contribute at a greater degree, as spatial cues, to the moment of spatial re-orientation?*”, are the following:

**H<sub>null</sub>:** Average isovist properties of all trials will be roughly equal during a time-period closer to the button-release moment and a time-period of equal duration before that.

**H<sub>spaciousness</sub>:** Average isovist properties of maximum area and maximum revelation will be higher for the time-period near to the button-release moment compared to the time period of equal duration before that.

**H<sub>complexity</sub>:** Average isovist properties of maximum visual control and minimum clustering coefficient will be higher and lower, respectively, for the time-period near to the button-release moment compared to the time period of equal duration before that.

The two competing hypotheses suggest that environmental cues that contribute to the event of interest can be described by either high values of area and revelation or, high values of visual control and low values of clustering coefficient. Therefore, for each time period (12s-9s, 9s-6s, 6s-3s, and 3s-0s) of each trial, the maximum values of revelation, area, visual control and minimum values of clustering coefficient were analysed. Table 4.2-4 shows the mean values of the isovist properties (averaged for each subject) for each time period.

Isovist Properties	Time Periods before button-release moment				
		12s-9s	9s-6s	6s-3s	3s-0s
Maximum Revelation	Mean	1195	1160	1177	1394
	Std. Error	58.20	73.59	60.34	91.90
Maximum Area	Mean	9415	9626	10036	10826
	Std. Error	610.43	609.69	571.88	628.18
Minimum Clustering Coefficient	Mean	0.667	0.670	0.667	0.643
	Std. Error	0.0079	0.0092	0.0089	0.0071
Maximum Visual Control	Mean	1.301	1.328	1.347	1.445
	Std. Error	0.029	0.025	0.025	0.020

Table 4.2-4. Average values of isovist properties for time windows of 3s duration

A one-way repeated measures ANOVA with a Greenhouse-Geisser correction<sup>28</sup> was used to examine whether there are significant differences among the means of the isovists values for the different time periods. The results show an overall significant difference in means for area, clustering coefficient and visual control [Area:  $F(1.66, 31.47) = 10.25$ ,  $p=0.001$ , Clustering Coefficient:  $F(2.16, 40.99) = 14.69$ ,  $p<0.001$ ; Visual Control:  $F(2.24, 42.60) = 12.10$ ,  $p < 0.001$ ]. There were no significant differences for the values of revelation [ $F(1.81, 34.34) = 2.85$ ,  $p = 0.08$ ]. Given that the main effect is significant for the three isovist properties, post hoc tests were used to isolate the specific time-periods where the means are different. As shown in Table 4.2-5, post-hoc pairwise comparisons using Bonferroni correction revealed that the means of area, clustering coefficient and visual control for the time period just before the response (3s-0s) are significantly different from the rest of the time periods (Figure 4.2-11). Within the 3s period before participants' decision to stop their movement at the location where they give their response, maximum values of area and visual control are significantly higher than during time period of an equal duration just before that and minimum values clustering coefficient are significantly lower (Table 4.2-4).

<sup>28</sup> The one-way repeated measures ANOVA assumes that the variances of the differences between the pairs of measurements for each level (e.g. time periods) are roughly equal. If this assumption (assumption of sphericity) is violated then SPSS adjusts the degrees of freedom automatically using the Greenhouse-Geisser or Huynh-Feldt corrections (Field, A. P., 2013).

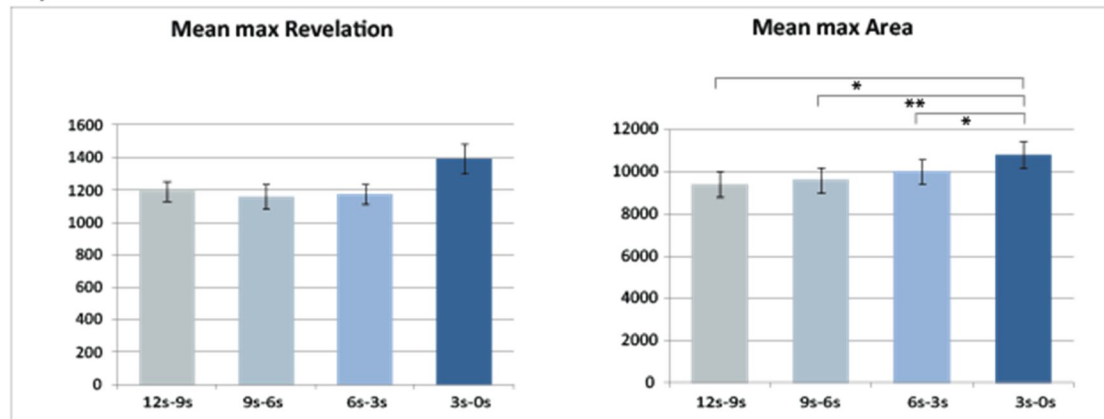
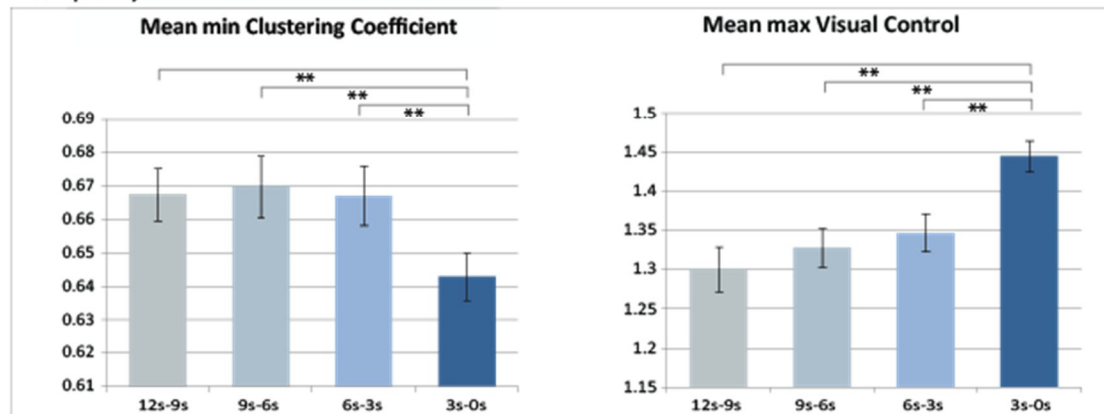
**Hspaciousness****Hcomplexity**

Figure 4.2-11. Bar charts of mean isovist values at four time--periods of 3s duration.

Isovist Properties	Pair wise comparisons		Mean Difference	Std. Error	p value
Maximum Area	3s-0s	6s-3s	790.39	253.17	0.034
		9s-6s	1200.22	305.35	0.005
		12s-9s	1411.65	398.50	0.013
Minimum Clustering Coefficient	3s-0s	6s-3s	-0.042	0.008	0.000
		9s-6s	-0.047	0.011	0.002
		12s-9s	-0.059	0.010	0.000
Maximum Visual Control	3s-0s	6s-3s	0.098	0.022	0.001
		9s-6s	0.117	0.025	0.001
		12s-9s	0.144	0.029	0.001

Table 4.2-5. Post-hoc comparisons for cases with significant main effects between time periods

To ascertain that any significant differences are not produced by variations in speed or in stationary behaviour, I have also examined and compared the peaks in isovist values for four segments of equal length<sup>29</sup> of distance travelled until the button-release (60m-45m, 45m-30m, 30m-15m and 15m-0m). Table 4.2-6 shows the mean values of the isovist properties for each segment (averaged for each subject).

<sup>29</sup> As mentioned earlier mean distance travelled for the 3s period is 14.92 virtual meters (SEM=0.50)

Isovist Properties	Distance segments before button-release moment				
		60m-45m	45m-30m	30m-15m	15m-0m
Maximum Revelation	Mean	1012	1081	1194	1429
	Std. Error	66	76	71	99
Maximum Area	Mean	8479	8783	9488	10749
	Std. Error	569.59	605.38	589.90	644.61
Minimum Clustering Coefficient	Mean	0.702	0.689	0.685	0.643
	Std. Error	0.0096	0.0095	0.0077	0.0065
Maximum Visual Control	Mean	1.200	1.223	1.273	1.441
	Std. Error	0.027	0.025	0.026	0.022

Table 4.2-6. Average values of isovist properties for distance segments of 15m length

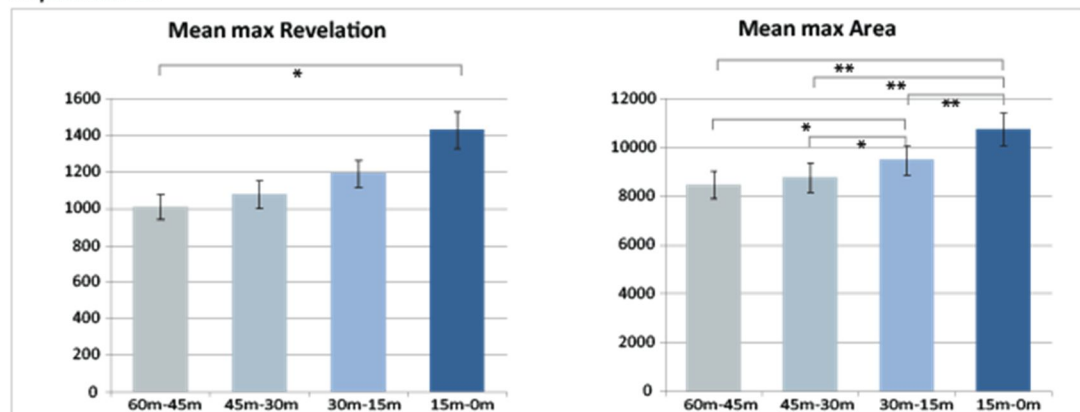
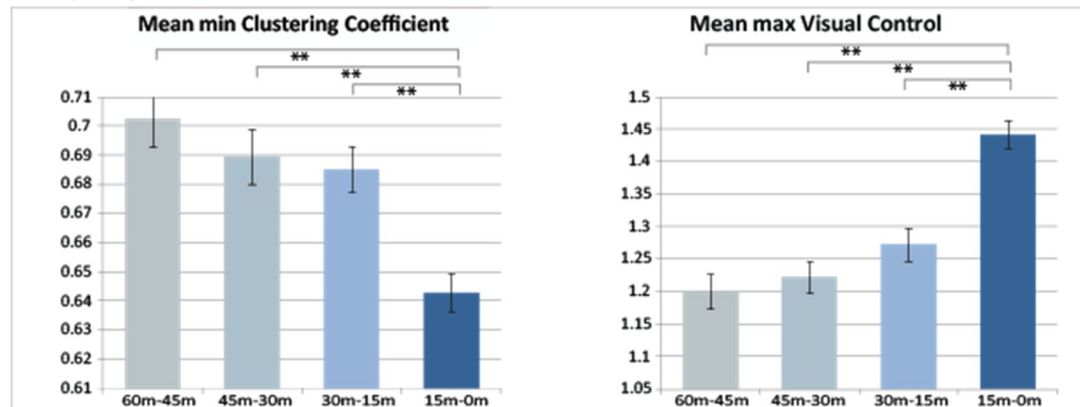
**Hspaciousness****Hcomplexity**

Figure 4.2-12. Bar charts of mean isovist values at four distance segments of 15m.

A one-way repeated measures ANOVA with a Greenhouse-Geisser correction was used to examine whether there are significant differences among the means of the isovists values for the different distance segments. There were significant difference in means for all isovist properties [Revelation:  $F(1.92, 36.50) = 5.55, p=0.009$ ; Area:  $F(1.47, 27.98) = 19.87, p<0.001$ , Clustering Coefficient:  $F(2.16, 40.99) = 14.69, p<0.001$ ; Visual Control:  $F(2.82, 53.62) = 32.31, p < 0.001$ ].

Post-hoc pairwise comparisons using Bonferroni correction, as shown in Table 4.2-7, indicate that the mean values of isovist revelation of the first segment (15m-0m) are only significantly different from the last segment (60m-45m) but not the rest of the distance segments. However, mean values of isovist area, clustering coefficient and visual control of the first segment just before the response (15m-0m) are significantly different from the rest of the distance segments (Figure 4.2-12). Similarly to the time-periods analysis, maximum values of area and visual control are significantly higher within 15m before participants' button-release than during segments of equal length of distance travelled just before that and minimum values clustering coefficient are significantly lower. The similar pattern that can be observed between the two ways of analysing the differences of mean isovist values, based on time-intervals and on distance segments, suggests that the significant differences observed between the main time-periods of interest (6s-3s and 3s-0s) are not the product of variations in speed or stationary behaviour. Therefore, further analysis is focused on these two time-windows of 6s-3s and 3s-0s.

Isovist Properties	Pairwise comparisons		Mean Difference	Std. Error	p value
Maximum Revelation	15m-0m	30m-15m	235.44	110.31	0.276
		45m-30m	348.47	135.63	0.113
		60m-45m	417.14	138.97	0.044
Maximum Area	15m-0m	30m-15m	1260.80	262.66	0.001
		45m-30m	1965.86	398.71	0.001
		60m-45m	2269.38	464.00	0.001
Minimum Clustering Coefficient	15m-0m	30m-15m	-0.042	0.008	0.000
		45m-30m	-0.047	0.011	0.002
		60m-45m	-0.059	0.010	0.000
Maximum Visual Control	15m-0m	30m-15m	0.168	0.030	0.000
		45m-30m	0.219	0.031	0.000
		60m-45m	0.242	0.029	0.000

Table 4.2-7. Post-hoc comparisons for cases with significant main effects between distance segments

The 2x1 repeated measures of ANOVA analysis for the two time-periods of 6s-3s and 3s-0s calculates the ratio of variability between the two time periods and the variability within each time-period among participants. The results show that the main effect for revelation across participants for the two time periods is not significant ( $F(1,19)=3.62$ ,  $p=0.072$ ) while for area ( $F(1,19)=9.75$ ,  $p=0.006$ ), clustering coefficient ( $F(1,19)=9.75$ ,  $p=0.006$ ) and visual control ( $F(1,19)=20.55$ ,

$p < 0.001$ ) the difference between the two time periods is statistically significant (Figure 4.2-13 bottom row and Figure 4.2-14 bottom row, respectively).

Grouping trials by participant shows clearly the variability in the data. As shown in Figure 4.2-13 and Figure 4.2-14 there is great variability for revelation and perhaps area as well, compared to the cases of clustering coefficient and visual control. The ratio of the standard deviation to the mean (coefficient of variation), that is the relative variability of the revelation and area values is greater than in the case of visual control and clustering coefficient. Coefficient of variation of individual trials for the time-period of 3s-0s is 1.30 and 0.87 for the revelation and area measurements but 0.23 and 0.26 for the clustering coefficient and visual control respectively.

Higher variability of the isovist values in these groups, suggests that in some trials, participants might have passed, for instance, by a location with much higher values of revelation or area, within the 3s period before button press, and in some others with relatively smaller maximum values. However, both types of trials lead to a the button-release moment. One possible explanation for this variability is that participants decided to stop and pressed the spacebar button for different reasons. Higher values of revelation and area appear at the locations where small streets intersect with big central streets. However, if one enters from a small street in the middle of a big street where no directional information is available then is highly likely that one will know more or less her location but, she will be confused about the heading direction. One possible explanation is that, in these trials, participants stop and press the spacebar button just to check the map (or study the map in relation to their path from the point of origin) rather than to give their response because they actually know where they are.

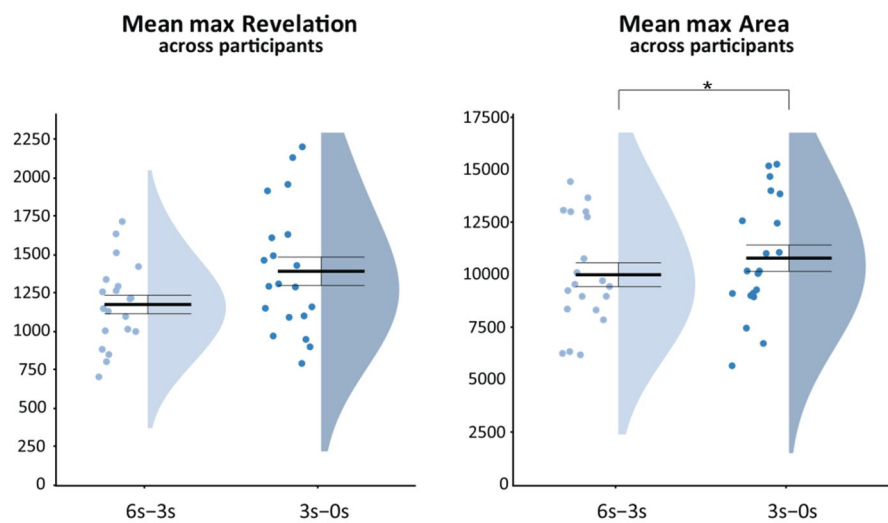
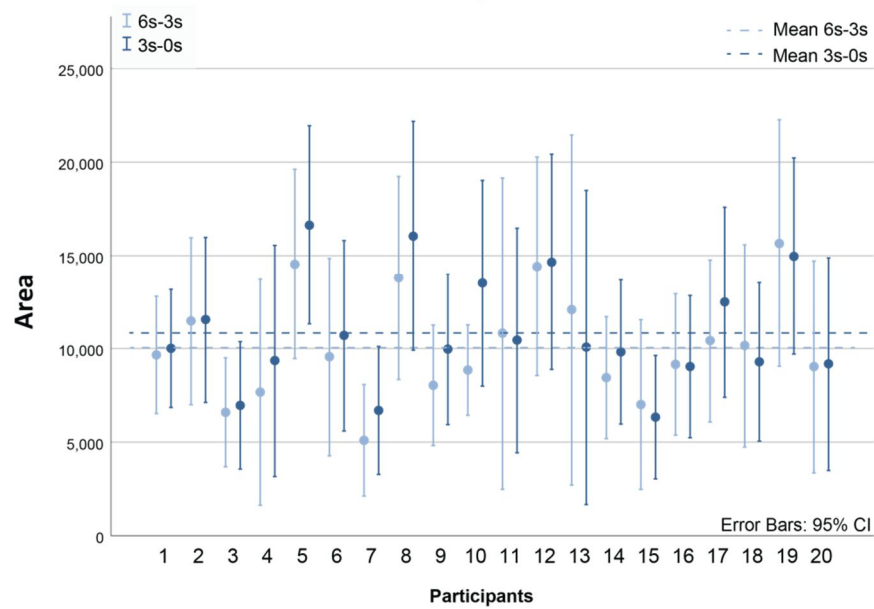
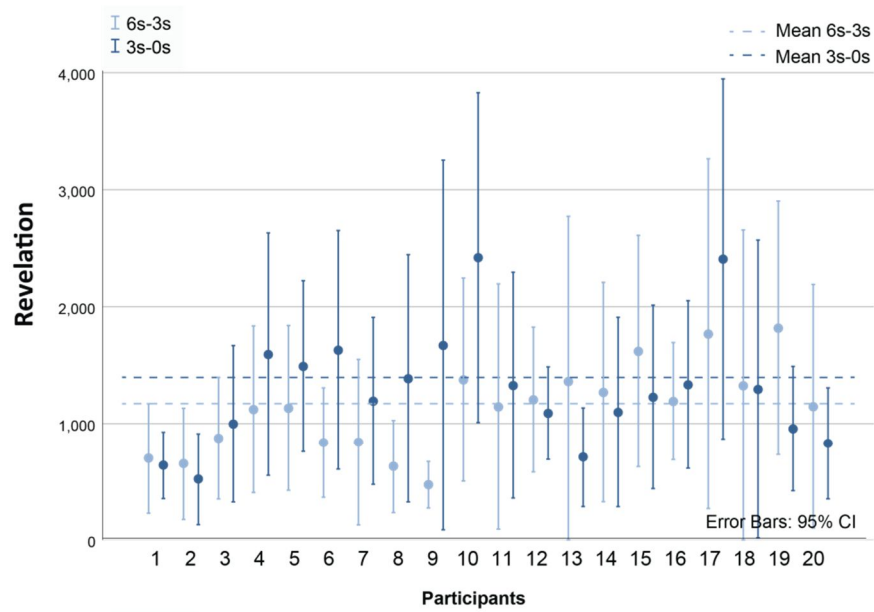


Figure 4.2-13. Variability of revelation and area values (Hspaciousness).



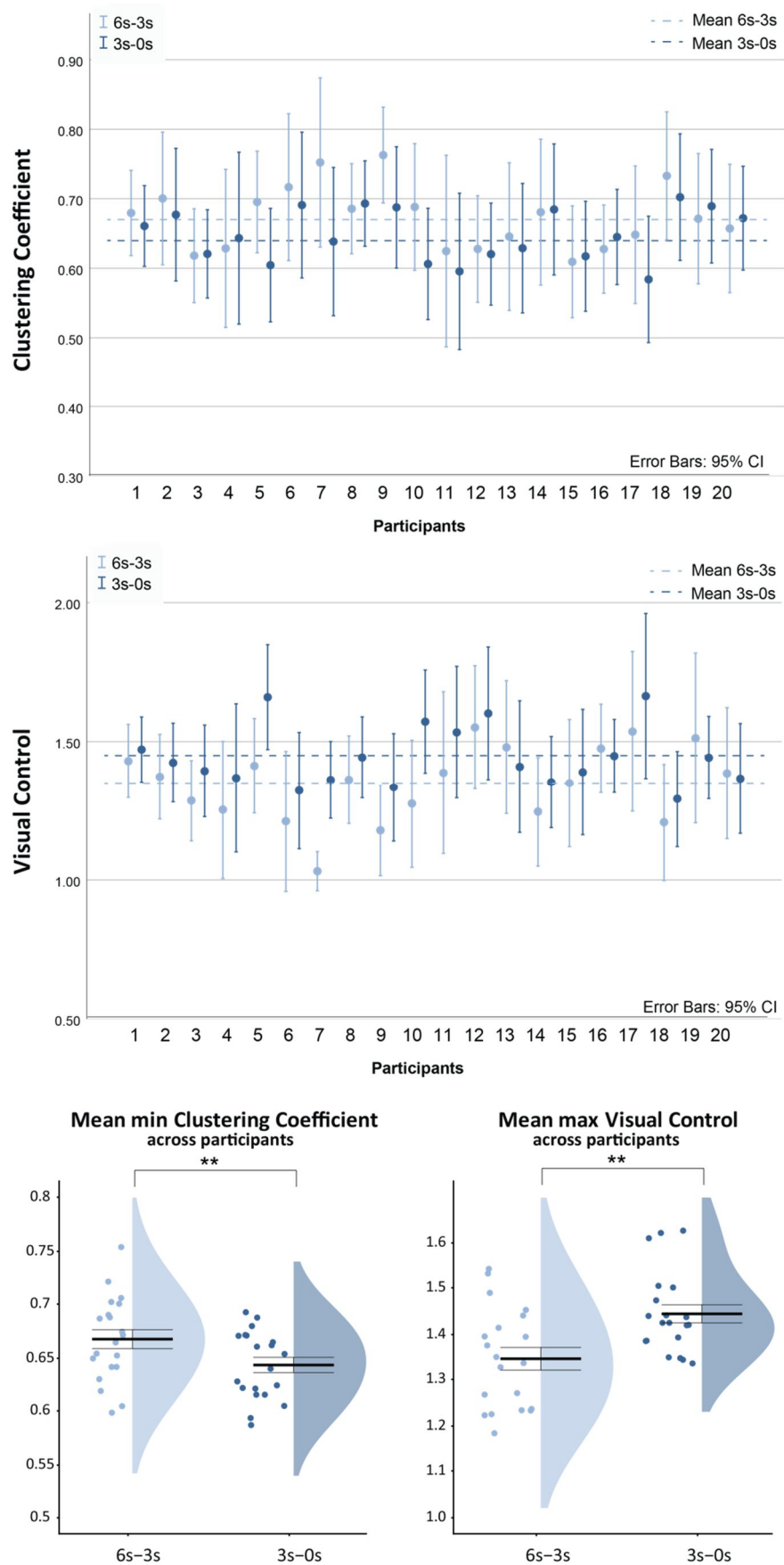


Figure 4.2-14. Variability of clustering coefficient and visual control values (Hcomplexity).

#### 4.2.4 Frequency distribution of button-release responses

This section explores the isovist values at the specific button-release location where participants stop in order to give their response. More specifically the analysis is focused on the frequency of button-release responses in relation to the range of values of the isovist properties of a bigger population of spatial locations, which includes (a) the point location encountered in each route and (b) point locations of the whole urban environment. In this way, we can examine which properties have the greatest tendencies in relation to the larger population of point locations for both cases and, therefore, to draw conclusions in regards to which of the two competing hypotheses is more likely to be the case. Therefore, the hypotheses for the research question *“In what sort of spaces is more likely for participants to release the movement button just before their response to the task?”* are the following:

**H<sub>null</sub>:** Button-release locations will have isovist values that are equally distributed with respect to the values of the whole system and the values of the point locations that were encountered through movement.

**H<sub>spaciousness</sub>:** High percentage of button-release locations will have values of isovist area and revelation that fall within the highest percentile ranks of the respective values across the whole system and the values of the point locations that were encountered through movement. That is, responses will occur at locations where there is a large amount of visual information and a big change in the amount of visual information in relation to its adjacent nodes.

**H<sub>complexity</sub>:** Responses will occur at visually dominant locations with a high degree of choice of movement in relation to its adjacent nodes and with multidirectional visual fields which 'promise' the gain of new visual information through movement. That is locations that fall within the highest bands of visual control and the lowest percentile ranks of clustering coefficient of the respective values of the whole system and the values of the point locations that were encountered through movement.

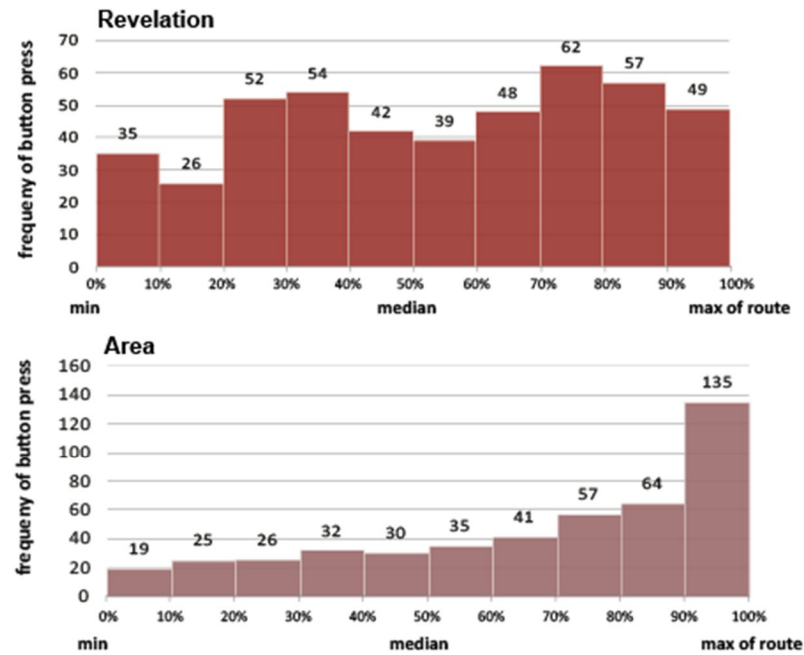
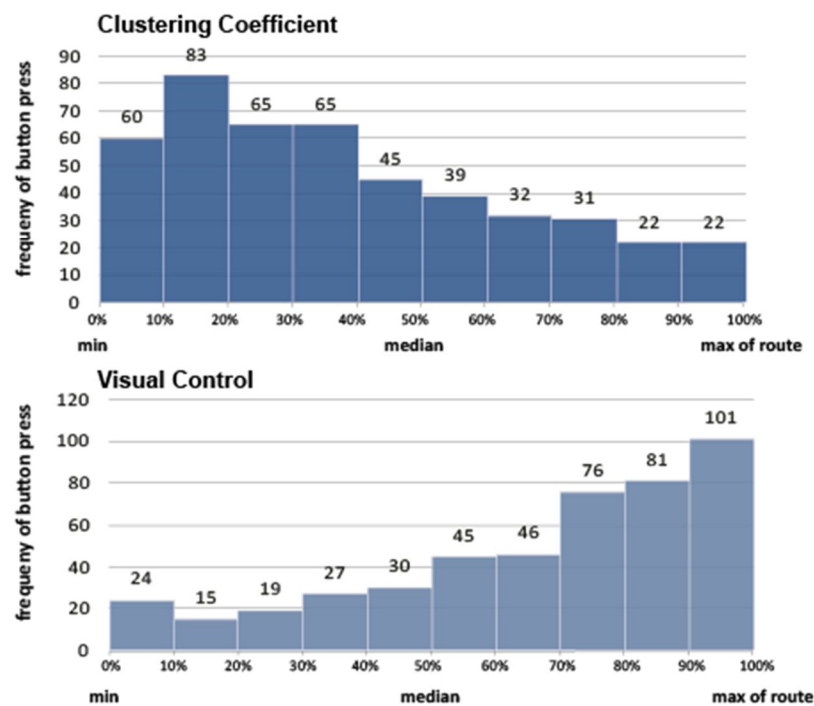
**A. Hspaciousness****B. Hcomplexity**

Figure 4.2-15. Count of isovist values at the button-release location based on the distribution of isovist values of each route. The isovist values at button release location are normalised in relation to the maximum value of each route ( $x/\text{route max}$ ). (A) Frequency distribution of revelation and area, Hspaciousness (B) Frequency distribution of clustering coefficient and visual control, Hcomplexity.

### **Isovist properties as percentiles of the whole route path in each trial**

The route-related frequency analysis illustrates the distribution of the spatial properties at the locations where individuals tend to stop more frequently in order to give their response to the orientation task. Therefore, it gives an initial idea of which locations are chosen as being more important for potential orientation within the population of locations of the whole route (Figure 4.2-15). The bar charts in Figure 4.2-15A show the distribution of the isovist properties of revelation and area at the button-release location. In the case of isovist area, there is a strong concentration at the top end of the 20% of the highest values (roughly 40% of the cases).

However, revelation values are more evenly distributed across the ten bands. The frequency distributions of both clustering coefficient and visual control, on the other hand, show clearer tendencies as a set (Figure 4.2-15B). Button-releases occur more frequently at locations with low clustering coefficient, with almost 30% of responses falling within the lowest 20% of the range of values of the locations that have been encountered through movement. Visual control values at these locations are concentrated at the top end, with almost 40% of responses above the 80% of the highest values.

### **Isovist properties as percentiles of the whole system**

Following a similar way of analysis as in the previous section, the analysis here highlights the kind of locations that participants pick up as more important out of the population of point locations of the whole system (city environment). The frequency distribution analysis of isovist area and revelation in relation to the whole system (Figure 4.2-16) reveals that there is no clear tendency among participants in choosing to give their response at locations, for example, with highest values of area or revelation, as would be expected if hypothesis one was true. The values of these properties at the button-release locations have, more or less, even distribution across the bands in both cases.

On the other hand, the cases of visual control and clustering coefficient (Figure 4.2-17), present a quite unambiguous image. There is again a clear tendency of values at the button-release location to fall within the 20% of the lowest clustering

coefficient values (more than 40% of the cases) and within the 20% of highest values of visual control (more than 50% of responses).

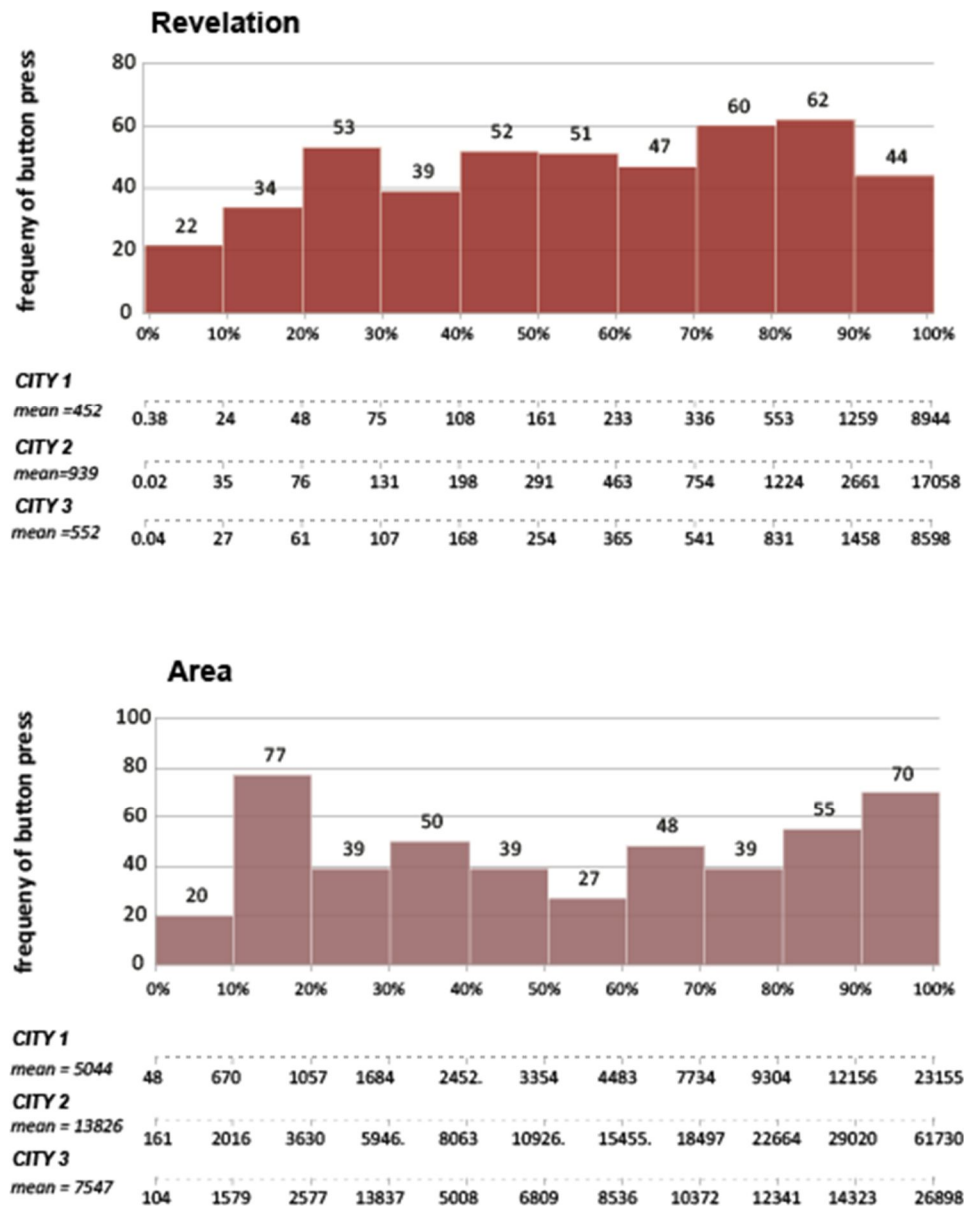


Figure 4.2-16 Count of isovist values at the button-release location based on the distribution of isovist values of the whole system (Hspaciousness). The isovist value at the button-release location is normalised in relation to the maximum value of each city ( $x/\text{city max}$ ).

The frequency distribution of the isovist values at the location where participants decided to stop to give their response to the task shows a trend towards lower values of clustering coefficient and higher values of visual control (Figure 4.2-17). The reverse trends in these two isovist measures highlight their negative correlation. Indeed as shown in Figure 4.2-18 they have a strong negative correlation in all three

environments. Interestingly, the properties of clustering coefficient and visual control seem to be more highly correlated with respect to the button-release location compared to the whole population of locations of the three virtual environments.

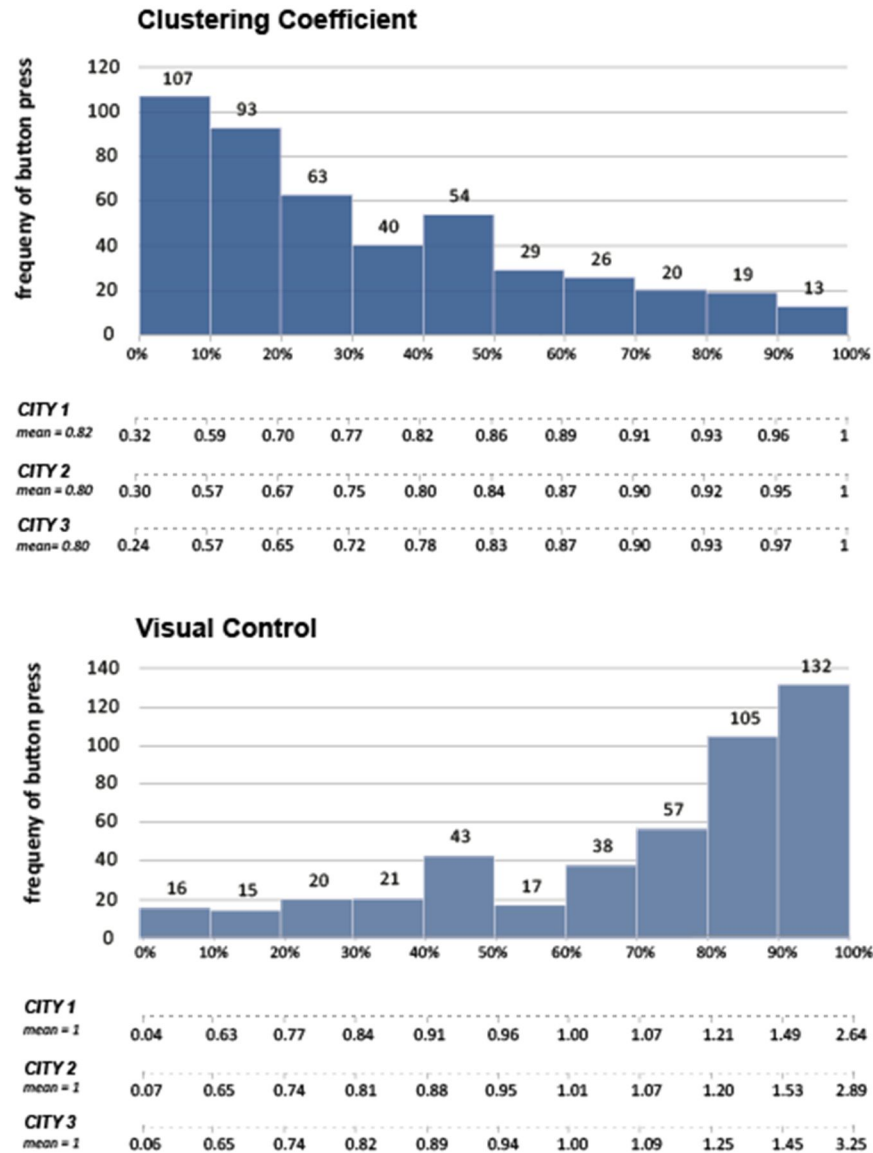


Figure 4.2-17. Count of isovist values at the button-release location based on the distribution of isovist values of the whole system (Hcomplexity). The isovist value at the button-release location is normalised in relation to the maximum value of each city ( $x / \text{city max}$ ).

The behavioural results and frequency distribution of participants' responses suggest, that participants show a preference for locations where there is a change in the complexity of the visual information. In addition, the values of clustering coefficient and visual control at the locations where participants chose to give their response, show stronger negative correlations than the population of all locations within the

three cities. This observation is rather in line with the discussion on the relation of these two measures in section 2.3.3 (Figure 2.3-1).

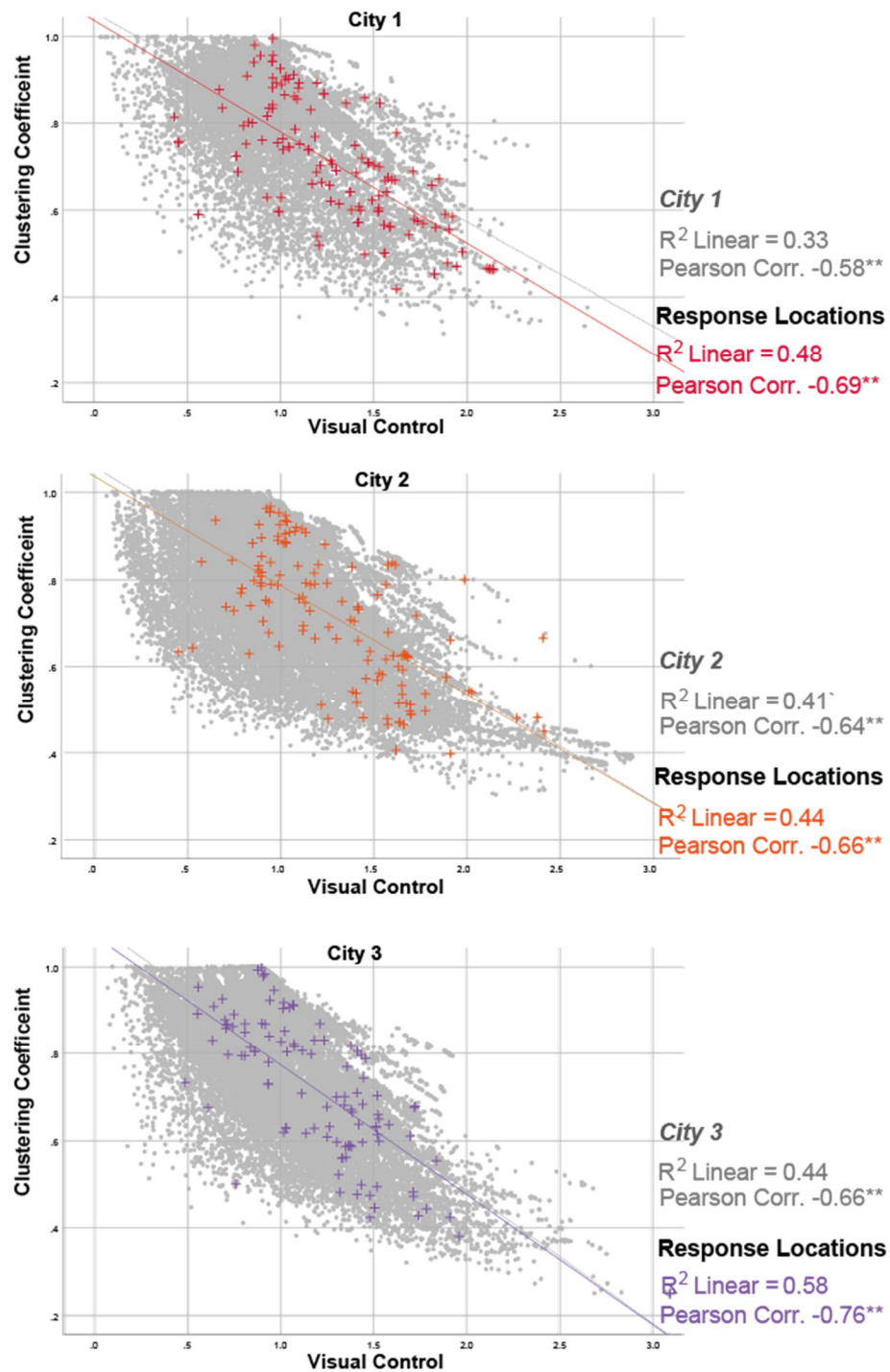


Figure 4.2-18: Correlations between visual control and clustering coefficient at locations of response in the three virtual Environments (\*\* p-value<0.01).

### 4.3 Spatial and Brain Dynamics Analyses

This section presents two types of analyses: a stimulus-related and response-related analyses of the EEG signal in relation to the isovist properties. The stimulus-related analysis examines initially the event-related potentials for two conditions of transitions in the perceived visuospatial information (for each isovist properties). That is, trials where a peak change in isovist values, within 3s before the button-release moment, falls (a) below versus (b) above the median peak change of all values. Then, the main focus is on these two conditions and their effect on the delta/theta power over frontocentral channels. The focus of the response-related analysis is (a) on the frontocentral channels (FC5 and FC6) where the test condition includes trials that exhibited an increase in mean theta power (event-related synchronisation, ERS) in the time window near the response; and (b) on the parietal channels (P7 and P8) where the test condition includes trials that exhibited a decrease in mean alpha power (event-related desynchronization, ERD).

#### 4.3.1 Stimulus-related analysis

The stimulus-related analysis examines the brain's response to peak changes in the isovist values just before the button-release moment. Processing of visuospatial information that is significant for navigation should be reflected by increases in frontocentral delta/theta activity. On the contrary, if changes in the visuospatial information are not significant then this will most likely result in the reduction of attentional and working memory demands, and in a decrease in delta/theta activity. If the null hypothesis is true, then mean change in EEG power (between a 3s period centred at the isovist change and a 3s period before that) will not be different between the cases of small versus large peak changes in isovist values (below versus above median). Alternatively, if changes in any specific isovist property contribute to the moment of spatial orientation, this should be manifested as a significant difference in EEG power between the two conditions. Therefore, the hypotheses for the stimulus-related research question *"Do peak changes in the visuospatial information (below-median versus above-median), as measured by the relevant isovist properties, have an effect on the delta/theta EEG power?"* are the following:



**H<sub>null</sub>**: The difference in mean delta/theta power will be roughly equal for the two conditions of isovist change (change in value below versus above median) for all properties.

**H<sub>spaciousness</sub>**: Mean delta/theta will be different for the two conditions (change in value below versus above median) for the isovist properties of revelation and area. Cases with a large change in the relevant isovist values will exhibit an increase in EEG power.

**H<sub>complexity</sub>**: Mean delta/theta will be different for the two conditions (change in value below versus above median) for the isovist properties of clustering coefficient and visual control. Cases with a large change in the relevant isovist values will exhibit an increase in EEG power.

The time-locking event for the stimulus-related analysis is a peak change in isovist values that precedes the button-release moment. Table 4.3-1 shows the descriptive statistics of these changes for isovist revelation, area, clustering coefficient, and visual control and the total number of cases that were included in the analysis.

Isovist Properties	Change in value (abs)					Total N
	minimum	maximum	median	mean	std. error	
Revelation	0.351	8455.97	225.76	666.33	67.67	312
Area	0.730	25030.04	439.52	1526.57	168.99	304
Clustering Coefficient	0.000	0.420	0.047	0.083	0.005	307
Visual Control	0.000	1.409	0.191	0.275	0.015	303

Table 4.3-1. Descriptive Statistics of changes in values of each isovist property

### Event-related potentials

The event-related potentials associated with this moment are presented in Figure 4.3-1 and Figure 4.3-2. The ERP waveforms are the result of the grand average across participants for the two conditions. The cases where the peak change in isovist values was below the median are in red and the cases where the change was above the median in blue. A paired t-test between individual points of the respective waveforms reveals certain time windows where there are significant differences ( $p < 0.05$ ). These are illustrated in the figures as grey rectangles. Visual inspection

suggests that the main changes occur at frontocentral channels, which are the focus of the time-frequency analysis that follows.

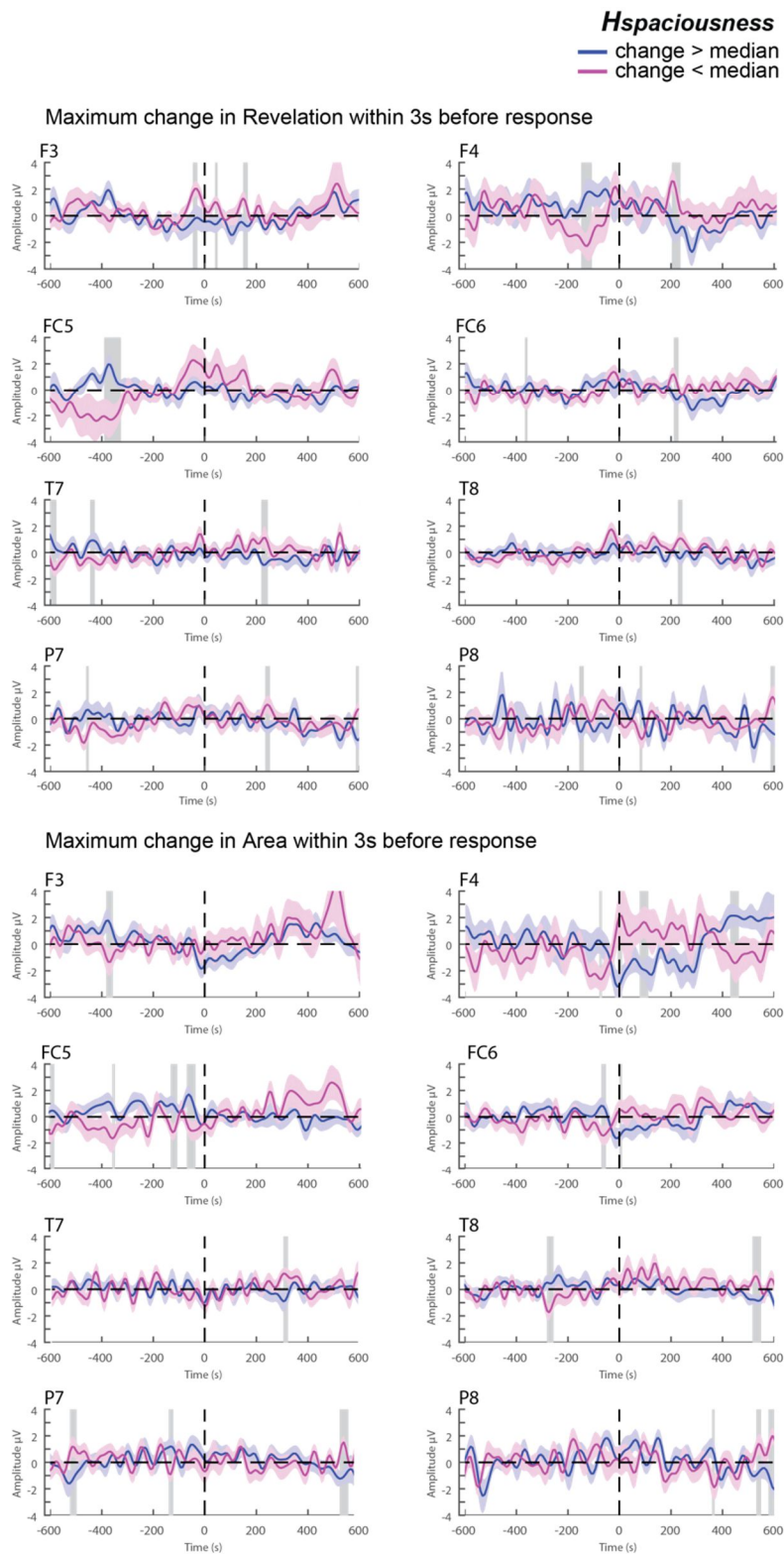


Figure 4.3-1. Event-related potentials for small and large peak changes in revelation and area. Grey areas indicate significant differences with  $p$  value  $< 0.05$ .

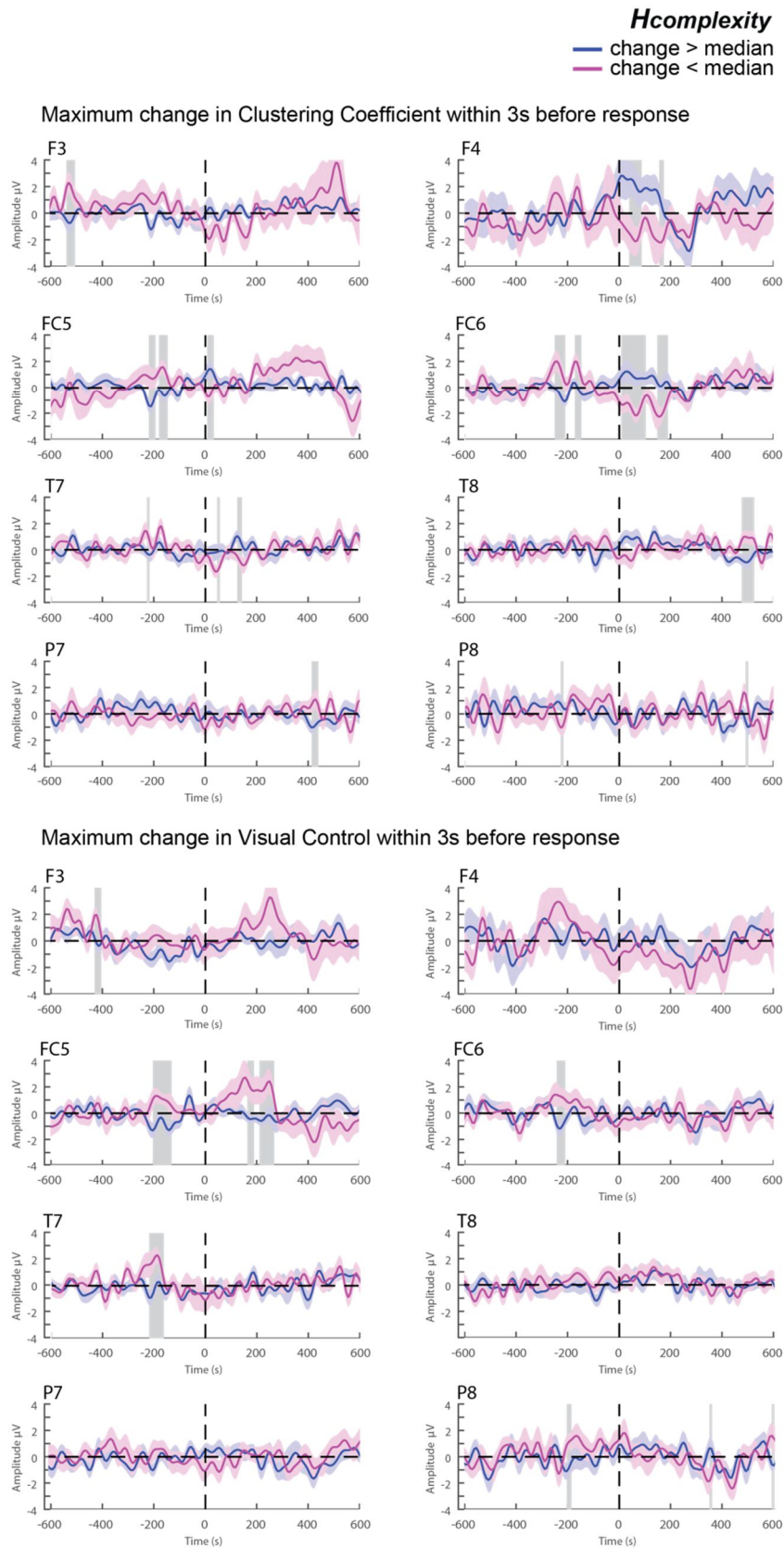


Figure 4.3-2. Event-related potentials for small and large peak changes in clustering coefficient and visual control. Grey areas indicate significant differences with  $p$  value  $< 0.05$ .

### Time-frequency analysis

The mean EEG delta/theta power difference (2-8Hz) over frontocentral channels is examined for the two conditions of peak isovist change and for each property. Table 4.3-2 shows the EEG power difference for these cases, averaged across both frontocentral channels and for each individual channel as well. The data presented in this table are the result of the average values of each participant.

Change in EEG power for delta/theta frequency band (2-8Hz)			Revelation	Area	Clustering Coefficient	Visual Control
average of FC5&FC6	1. < median isovist change	Mean	-0.374	-0.574	-0.651	-0.443
		std.error	0.236	0.191	0.231	0.171
		Median	-0.137	-0.466	-0.521	-0.167
	2. > median isovist change	Mean	0.198	0.073	0.139	-0.069
		std.error	0.092	0.153	0.180	0.185
		Median	0.115	0.034	0.220	0.020
left fronto-central (FC5)	1. < median isovist change	Mean	-0.273	-0.435	-0.453	-0.235
		std.error	0.173	0.128	0.173	0.127
		Median	-0.081	-0.280	-0.198	-0.096
	2. > median isovist change	Mean	0.197	0.050	0.141	-0.020
		std.error	0.098	0.071	0.103	0.080
		Median	0.149	0.024	0.023	-0.014
right fronto-central (FC6)	1. < median isovist change	Mean	-0.473	-0.736	-0.887	-0.690
		std.error	0.339	0.337	0.357	0.304
		Median	-0.264	-0.262	-0.788	-0.159
	2. > median isovist change	Mean	0.259	0.110	0.154	-0.101
		std.error	0.220	0.278	0.308	0.323
		Median	0.410	0.230	0.173	-0.071

Table 4.3-2. Mean change in delta/theta power over frontocentral channels for all four cases of isovist measures.

A non-parametric Friedman test<sup>30</sup> was used to examine the differences in the average EEG power -across both frontocentral channels- between the two conditions, for all four isovist properties (Figure 4.3-3. Mean delta/theta power difference averaged over both frontocentral channels for the two conditions of peak changes in isovist values Figure 4.3-3). The Friedman test found a significant difference in mean EEG power between the two isovist conditions [ $\chi^2(7) = 31.32$ ,  $p < 0.001$ ]. Wilcoxon tests, with a Bonferroni correction, were used to follow up this finding. There are no significant differences in EEG power between trials with small (Mdn = -0.14db) versus large (Mdn = 0.12db) peak changes in the values of revelation ( $z = -2.28$ , adjusted  $p = 0.09$ ,  $r = -0.36$ ) nor between trials with small (Mdn = -0.17db) versus

<sup>30</sup> The Shapiro-Wilk test of normality ( $p < 0.05$ ) revealed that data are not normality distributed.

large (Mdn = 0.02db) peak changes in values of visual control ( $z = -2.05$ , adjusted  $p = 0.16$ ,  $r = -0.33$ ).

However, in the case of isovist area there is a trend for trials with small peaks changes (Mdn = -0.47db) to show a decrease in EEG power compared to trials with large peak changes (Mdn = 0.04db) but the difference does not reach significance ( $z = -2.46$ , adjusted  $p = 0.06$ ,  $r = -0.39$ ). On the other hand, there is a significant difference ( $z = -2.61$ , adjusted  $p = 0.04$ ,  $r = -0.41$ ) between trials with small peak changes in values of clustering coefficient, which exhibit a decrease in EEG power (Mdn = -0.52db) compared with trials with large peak changes, which exhibit an increase (Mdn = 0.22db).

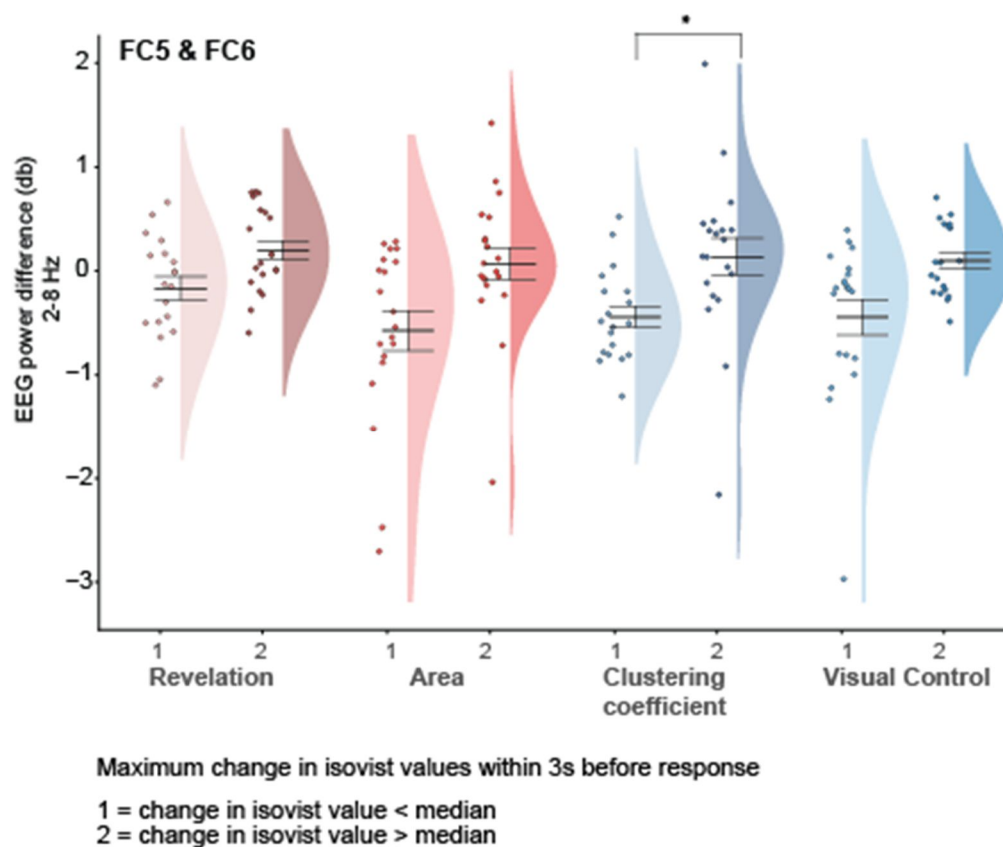


Figure 4.3-3. Mean delta/theta power difference averaged over both frontocentral channels for the two conditions of peak changes in isovist values \*  $p < 0.05$ , Wilcoxon test

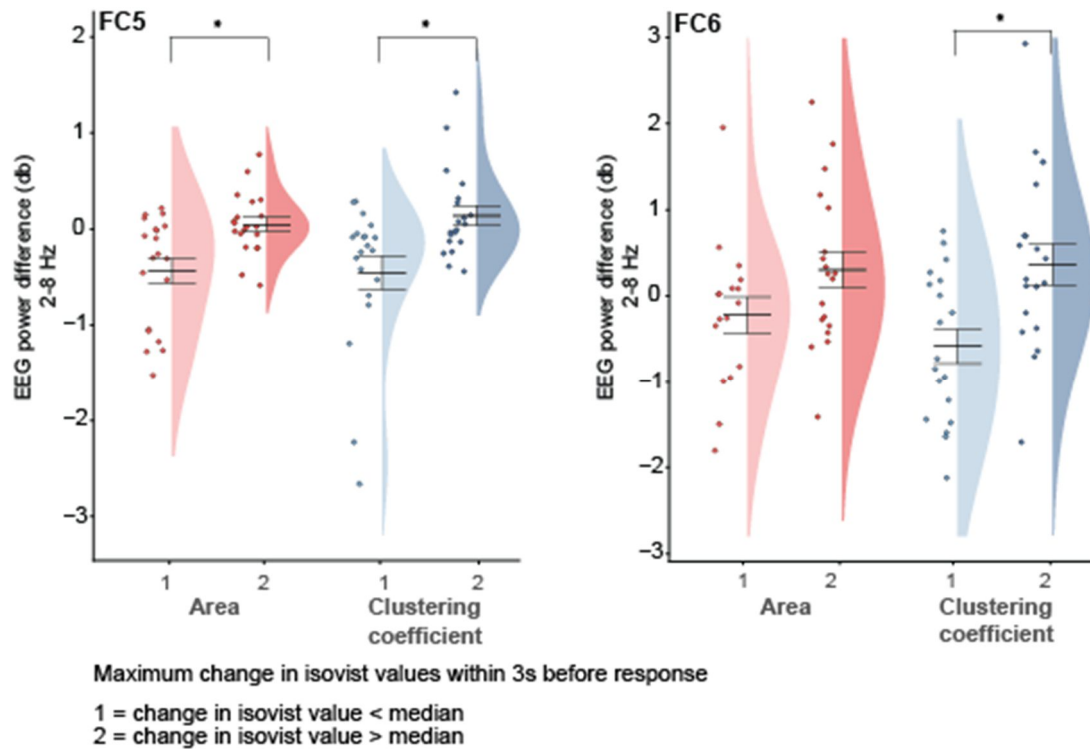


Figure 4.3-4. Mean delta/theta power averaged over left (FC5) and right (FC6) frontocentral channels for the two conditions of peak changes in isovist values. \*  $p < 0.05$ , Wilcoxon test

To further investigate the differences in EEG power, as a response to sudden changes in the visuospatial information, I also examined the EEG data from each individual frontocentral channel, FC5, and FC6 (Figure 4.3-4). The Wilcoxon tests, as described in the previous paragraph, found that differences in mean EEG power are significant only for trials that are time-locked to changes of clustering coefficient. But, there is also a trend towards a decrease in theta power for trials with small changes in the values of area. Thus, the focus of the analysis that follows is on these two isovist properties.

The Friedman test found significant difference in mean EEG power for both FC5 and FC6 channels [ $\chi^2(3) = 12.30$ ,  $p = 0.006$ ,  $\chi^2(3) = 9.29$ ,  $p = 0.026$ , respectively]. The post-hoc Wilcoxon tests revealed significant differences for Clustering Coefficient, for both FC5 and FC6 channels (FC5:  $z = -2.69$ , adjusted  $p = 0.014$ ,  $r = -0.43$ ; FC6:  $z = -2.35$ , adjusted  $p = 0.037$ ,  $r = -0.37$ ). There is a decrease in mean delta/theta power for trials time-locked to changes in values of clustering coefficient that fall below the median, for both FC5 (Mdn =  $-0.20$  db) and FC6 (Mdn =  $-0.79$  db)

compared with trials where the peak change is large, which results in an increase in delta/theta power (FC5: Mdn = 0.03 db; FC6: Mdn = 0.17 db).

In the case of isovist area, there is a decrease in mean delta/theta power at the left frontocentral channel (FC5) for trials with a small change in isovist values (Mdn = -0.28 db) compared with trials with a large peak change in isovist values (Mdn = 0.02 db) and this difference was found to be significant ( $z = -2.58$ , adjusted  $p = 0.02$ ,  $r = -0.41$ ). However, there is no significant difference for the mean delta/theta power at the right frontocentral electrode (FC6:  $z = -1.94$ , adjusted  $p = 0.10$ ,  $r = -0.31$ ).

The results here suggest that there is a stronger relationship between the peak changes in clustering coefficient values and the change in the delta/ theta power as opposed to changes in values of area. The differences in EEG power are statistically significant when examining each frontocentral channel separately and when looking at the averaged of both channels, as opposed to area which shows a significant decrease in power for trials with a small peak change in isovist values, only at the left frontocentral channel. Negative peaks of clustering coefficient values that fall above the median of absolute values are associated with increases in frontocentral delta/theta power. This effect is more pronounced at the right electrode, consistent with studies on navigation showing greater activity at the right hemisphere.

#### 4.3.2 Response-related analysis

The response-related analysis examines the differences in isovist values at the button-release location based on participants' brain dynamics during a 3s period before the event of interest. To ascertain which set of isovist properties is related to the Aha! experience of spatial re-orientation their mean values, averaged across subjects, are compared for two conditions: (a) alpha parietal decrease and theta frontocentral increase in EEG power; and (b) alpha parietal increase and theta frontocentral decrease in EEG power. If the null hypothesis is true, then the mean values of each isovist property will not differ between conditions. Alternatively, if changes in any specific isovist property contribute to the moment of spatial re-orientation, this should be manifested as a significant difference in the mean value of that property between the alpha decrease/theta increase and alpha increase/theta decrease conditions. Therefore, the hypotheses for the research question “*What are*

*the visuospatial conditions that elicit the expected brain dynamics, which are assumed to be related to the Aha moment of re-orientation?” are the following:*

**H<sub>null</sub>:** Average isovist properties of the trials will be roughly equal for the alpha decrease/theta increase and alpha increase/theta decrease conditions.

**H<sub>spaciousness</sub>:** Average isovist properties of area and revelation at the button-release location will be higher for the alpha decrease /theta increase cases compared to the alpha increase/theta decrease cases.

**H<sub>complexity</sub>:** Average isovist properties of visual control and clustering coefficient at the button-release location will be higher and lower respectively, for the alpha decrease /theta increase cases compared to the alpha increase/theta decrease cases.

### **Topographical scalp maps**

A visual representation of the brain dynamics of a sample of trials that belong to the two conditions of interest is presented in Figure 4.3-5. The EEG power of the alpha (8-12Hz) and theta (4-7Hz) bands at each channel is plotted on a topographical map that represents the surface of the human scalp. The data were interpolated using an eeglab command (topoplot) which 'calculates' the power between the electrodes to cover the whole scalp map. The topographical maps show trials from three participants that belong to the different conditions. The trials that belong to condition A exhibited both a decrease in mean alpha power at parietal channels and an increase in mean theta at frontocentral. The trials in condition B (Figure 4.3-5 B) have occurred at locations where the isovist values of interest are close to the average isovist values of the environments and in two of the cases values of clustering coefficient are a bit higher than average. Additionally, in these cases, the brain dynamics do not show many similarities. On the contrary, the trials in condition A (Figure 4.3-5 A) share a rather similar pattern of brain dynamics and all have low values of clustering coefficient and high visual control.



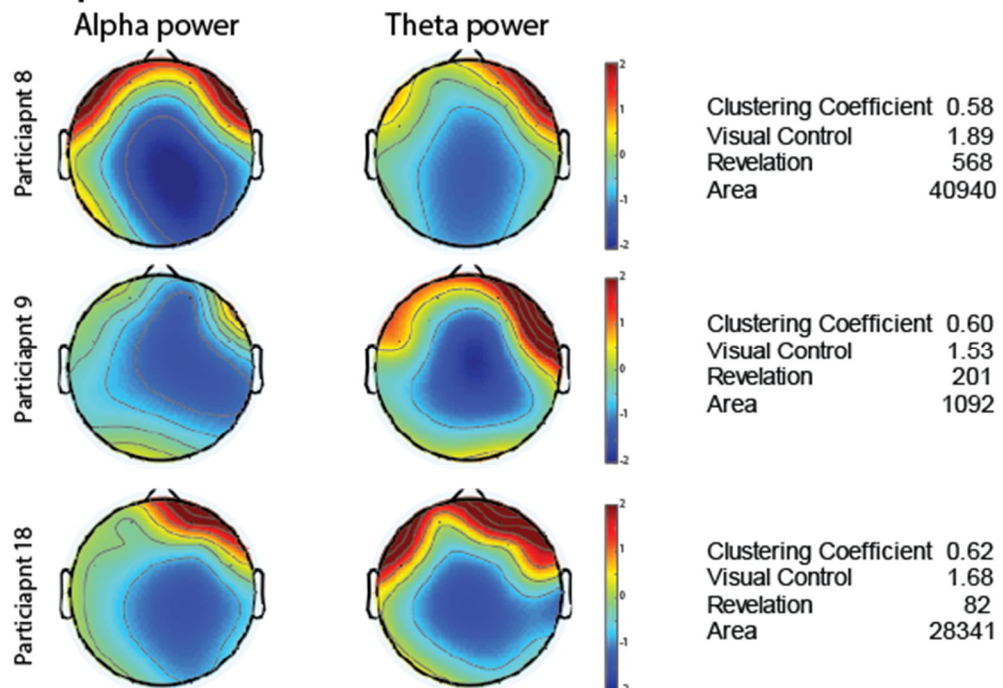
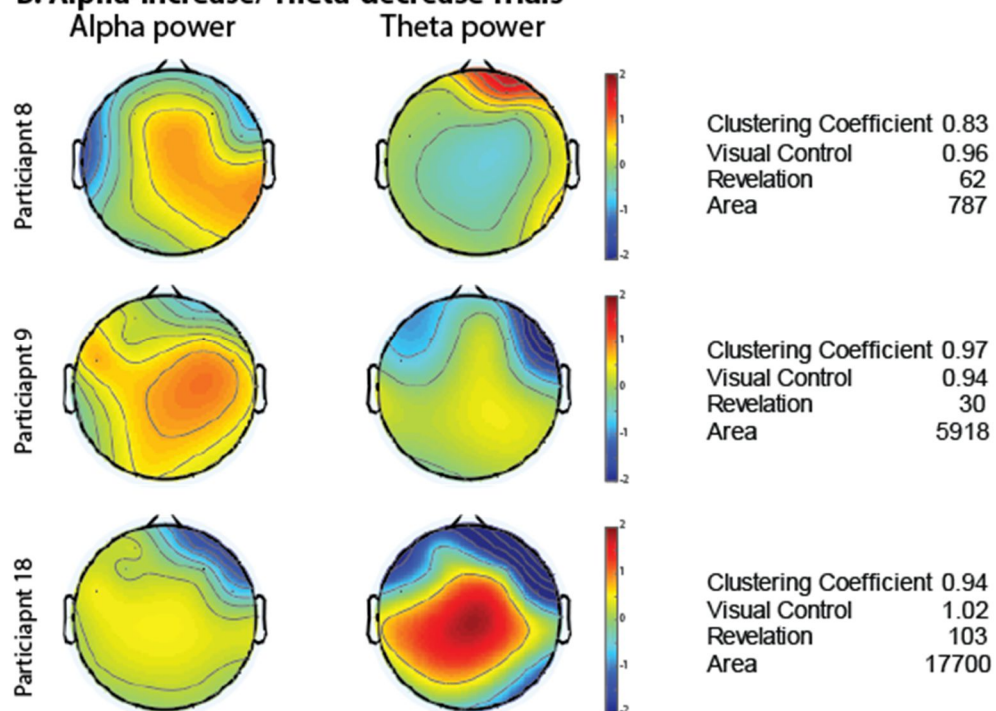
**A. Alpha-decrease/ Theta-increase Trials****B. Alpha-increase/ Theta-decrease Trials**

Figure 4.3-5. Topographical scalp maps of trials from 3 participants. The figure also shows the respective isovist values of clustering coefficient, visual control, revelation and area at the button-release location of each trial.

### Time-frequency analysis

To ascertain which set of isovist properties is related to the moment of spatial-reorientation, and thus test which hypothesis is better supported by the collected data, their mean values at the button-release location are compared across the two conditions of interest. To examine the relationship between the relevant isovist properties and the changes in EEG power, this first part of the analysis includes only cases where there is either a decrease (ERD) or an increase (ERS)<sup>31</sup> (a) of alpha power at both parietal channels and/or (b) of theta power at both frontocentral electrodes. The isovist properties of each condition are averaged separately for each participant. Table 4.3-3 and Table 4.3-4 show the relevant descriptive statistics.

Firstly, the mean values of the isovist properties at the button-release location for the test condition (alpha parietal decrease/theta frontocentral increase) are compared against the mean values of the isovist properties of all three virtual environments (Table 4.3-5) using a one-sample t-test (Table 4.3-6). The one-sample t-test (Table 4.3-6) found that the mean values of revelation and area for the test conditions, do not have a significant difference from the mean values of all locations of the three cities [ $t(19) = -0.77$ ,  $p = 0.45$ ;  $t(19) = -0.45$ ,  $p = 0.66$ ]. This suggest that trials that fall within the test conditions do not have higher values of revelation and area than the average, as one would expect if *Hspaciousness* was true. On the other hand, for trial that exhibited alpha parietal decrease, clustering coefficient values (mean = 0.68, SEM = 0.02) are significantly lower [ $t(19) = -7.35$ ,  $p < 0.001$ ] than the average (mean = 0.80, SEM < 0.001) and visual control values (mean = 1.30, SEM = 0.05) are significantly higher [ $t(19) = 5.63$ ,  $p < 0.001$ ] than the average (mean = 1.00, SEM = 0.001). The same pattern is present for the trials that exhibited theta frontocentral increase. Again. clustering coefficient values (mean = 0.68, SEM = 0.02) are significantly lower [ $t(19) = -6.93$ ,  $p < 0.001$ ] than the average and visual control values (mean = 1.32, SEM = 0.05) are significantly higher [ $t(19) = 6.97$ ,  $p < 0.001$ ].

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<sup>31</sup> ERS stands for event-related synchronisation, a term often used to explain an increase in power in a certain frequency band and ERD for event-related desynchronisation corresponding to a decrease in power.

## Analyses of Spatial Behaviour and Brain Dynamics

Parietal alpha power (P7 & P8)		Median across subjects	Mean across subjects	Std. Deviation	Std. Error Mean
Revelation	$\alpha$ decrease	625	654	392	88
	$\alpha$ increase	395	618	674	151
Area	$\alpha$ decrease	7927	9049	5140	1149
	$\alpha$ increase	10327	10403	5141	1150
Clustering Coefficient	$\alpha$ decrease	0.69	0.68	0.07	0.02
	$\alpha$ increase	0.73	0.74	0.08	0.02
Visual Control	$\alpha$ decrease	1.27	1.30	0.24	0.05
	$\alpha$ increase	1.21	1.26	0.25	0.06

Table 4.3-3. Descriptive statistics of isovist values averaged across participants for the alpha-decrease and alpha-increase conditions (P7 & P8)

Frontocentral theta power (FC5 & FC6)		Median across subjects	Mean across subjects	Std. Deviation	Std. Error Mean
Revelation	$\theta$ increase	744	684	374	84
	$\theta$ decrease	497	639	517	116
Area	$\theta$ increase	8183	10002	6429	1438
	$\theta$ decrease	8087	9747	4700	1051
Clustering Coefficient	$\theta$ increase	0.69	0.68	0.08	0.02
	$\theta$ decrease	0.75	0.74	0.07	0.02
Visual Control	$\theta$ increase	1.33	1.32	0.21	0.05
	$\theta$ decrease	1.21	1.24	0.27	0.06

Table 4.3-4. Descriptive statistics of isovist values averaged across participants for the theta-increase and theta-decrease conditions (FC5 & FC6)

Isovist properties of virtual cities	Median	Mean	Std. Deviation	Std. Error Mean
Revelation	249	722	1284	4.24
Area	7850	10164	9063	29.95
Clustering Coefficient	0.84	0.80	0.14	0.0005
Visual Control	0.95	1.00	0.34	0.0011

Table 4.3-5. Descriptive statistics of isovist values across the three virtual cities.

One-Sample Statistics		t	df	p value (Bonf. adj.)
Parietal alpha decrease	Revelation	-0.772	19	0.450
	Area	-0.970	19	0.344
	Cl. Coefficient	-7.354	19	0.000
	Visual Control	5.632	19	0.000
Frontocentral theta increase	Revelation	-0.449	19	0.658
	Area	-0.112	19	0.912
	Cl. Coefficient	-6.927	19	0.000
	Visual Control	6.972	19	0.000

Table 4.3-6. One-sample t-test results of differences between test conditions and cities' averages.

A repeated measures ANOVA (2 x 2; conditions by set of channels) was used to test for differences between test (parietal alpha decrease/frontocentral theta increase) and control (parietal alpha increase/frontocentral theta decrease) conditions as recorded by the two sets of parietal (P8 & P7) and frontocentral channels (FC5 & FC6) for the cases of area, clustering coefficient and visual control. A non-parametric Friedman test was used to examine these differences in the case of revelation, since the Shapiro-Wilk test of normality ( $p < 0.05$ ) revealed that data, in this case, are not normality distributed (Figure 4.3-6).

The analysis of variance found a significant effect of condition in the case of clustering coefficient for the two sets of channels [ $F(1,19) = 10.55$ ,  $p = 0.004$ ]. Clustering coefficient is significantly lower [ $t(19) = -2.39$ ,  $p = 0.027$ ] for trials with a parietal alpha decrease (mean = 0.68, SEM = 0.02) compared to the parietal alpha increase condition (mean = 0.74, SEM = 0.02). Similarly, clustering coefficient is significantly lower [ $t(19) = -2.23$ ,  $p = 0.038$ ] for the frontocentral theta increase condition (mean = 0.68, SEM = 0.02) compared to trials that exhibited a frontocentral theta decrease (mean = 0.74, SEM = 0.02). The repeated measures ANOVA found no significant effect of condition in the case of area [ $F(1,19) = 0.19$ ,  $p = 0.67$ ] nor in the case of visual control [ $F(1,19) = 2.34$ ,  $p = 0.14$ ]. No significant difference was found in the mean values of revelation between the two conditions or the two sets of channels [ $\chi^2(3) = 1.46$ ,  $p = 0.69$ ].

The previous analysis was focused on the cases where the EEG power exhibited either a decrease or an increase at both left and right channels. To include more trials in the comparison and to examine whether there are differences between the two hemispheres in the two conditions, the classification of trials is now based on the change of mean EEG power at each individual electrode: P7 and P8 for the alpha band and FC5 and FC6 for the theta band.

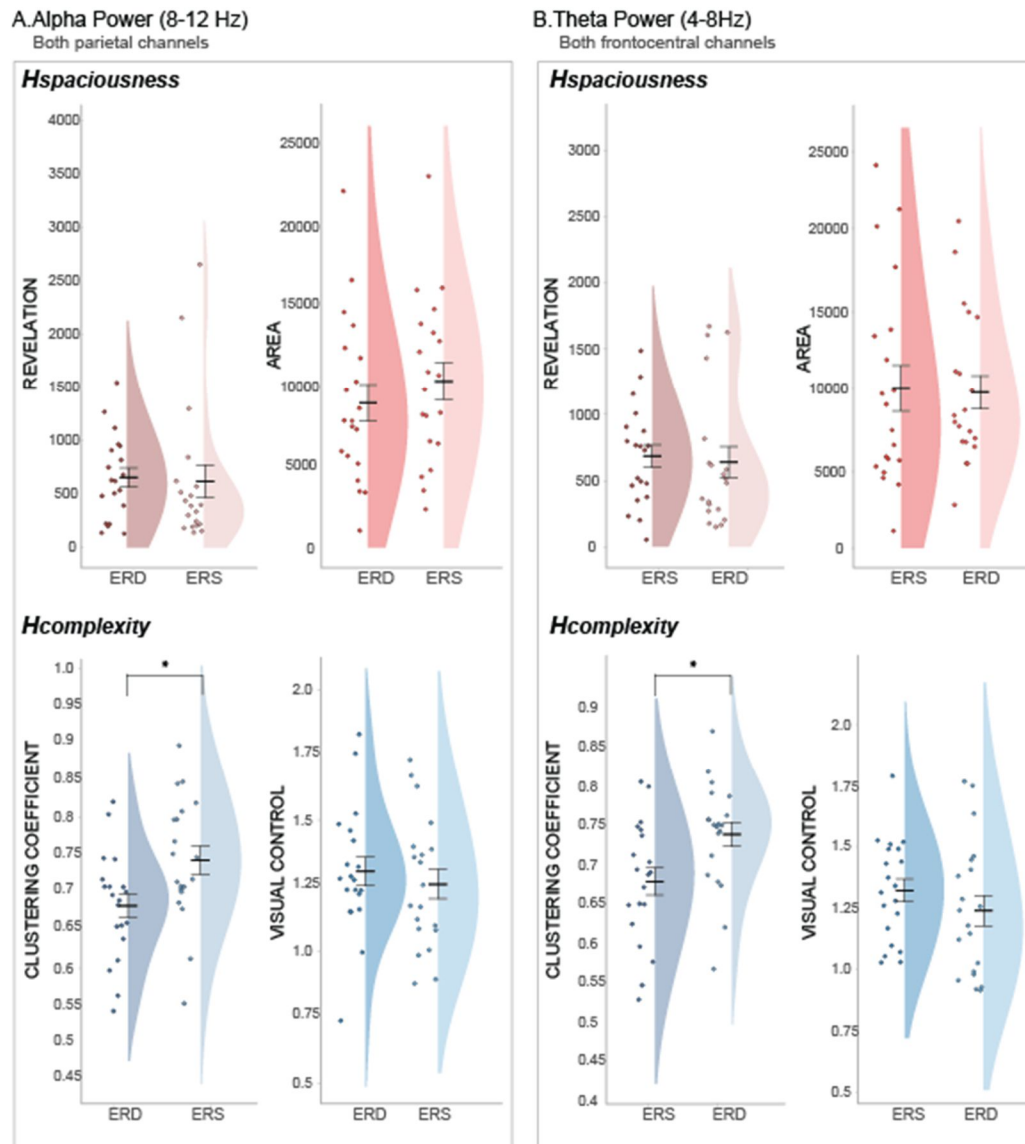


Figure 4.3-6. Mean isovist values for test and control conditions (A) alpha ERD and ERS at both parietal channels (P7&P8) and (B) theta ERS and ERD at both frontocentral channels (FC5&FC6). Figure shows the effect of condition (2x2 ANOVA). \*  $p < 0.05$ .

A repeated-measures ANOVA (2 x 4; conditions by channels) was used to test for differences between the two conditions (test versus control) and the four channels of interest (P8, P7, FC5, and FC6) for the cases of area, clustering coefficient, and visual control. A non-parametric Friedman test was used to examine these differences in the case of revelation, since the Shapiro-Wilk test of normality ( $p < 0.05$ ) revealed that data, in this case, are not normality distributed.

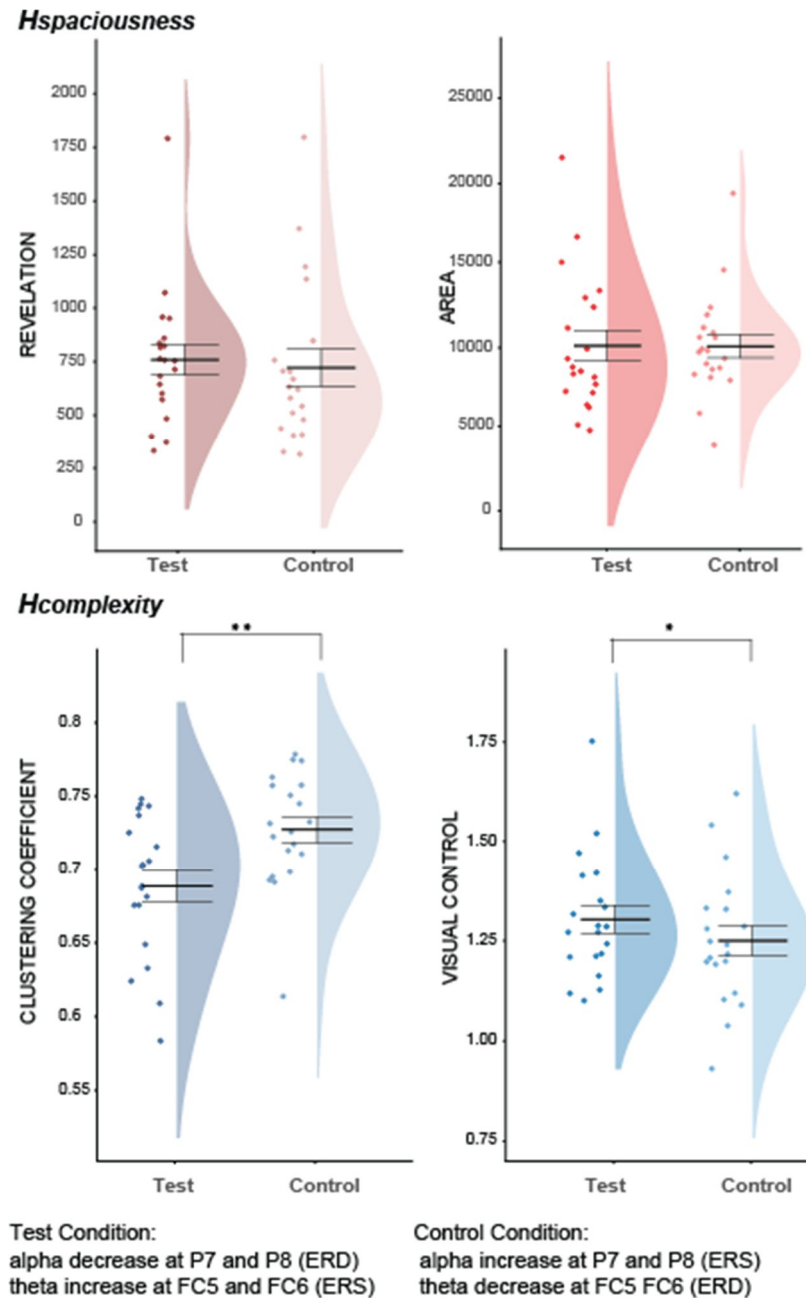


Figure 4.3-7. Mean isovist values for test (alpha-decrease/theta increase) and control (alpha-increase/theta decrease) conditions averaged across P7, P8, FC5 and FC6. Figure shows the effect of condition (2x4 ANOVA). \*  $p < 0.05$ , \*\* $p < 0.01$

The Friedman test found no significant difference in the mean values of revelation between the two conditions at the four channels of interest [ $\chi^2(7) = 5.70$ ,  $p < 0.58$ ]. The repeated measures ANOVA found no significant effect of condition in the values of area [ $F(1,19) = 0.002$ ,  $p = 0.96$ ]. However, there was a significant main effect of condition for the cases of clustering coefficient [ $F(1,19) = 16.07$ ,  $p < 0.001$ ] and visual control [ $F(1,19) = 6.44$ ,  $p = 0.02$ ]. The average values of each isovist

measures, across the four channels of interest and for the two conditions, are presented in Figure 4.3-7. Clustering coefficient is significantly lower [ $t(19) = -4.01$ ,  $p < 0.001$ ] for the test conditions (mean=0.69, SEM=0.011) compared to the control conditions (mean=0.73, SEM=0.009). Also, visual control is significantly higher [ $t(19) = 2.54$ ,  $p = 0.02$ ] for the test conditions (mean=1.30, SEM=0.04) compared to the control conditions (mean=1.25, SEM=0.04).

The Friedman's test and the 2X4 ANOVA reveal that there are no significant differences in the values of revelation and area, respectively, between the two conditions or the four channels. Thus, follow up tests do not include these two isovist properties. However, to facilitate visual comparison, Figure 4.3-8 and Figure 4.3-9 included the cases of both revelation and area. Subsequent analyses are focused on each individual channel. The classification of trials into the two conditions is again based on the change of mean power at each individual electrode, that is the P7 and P8 for the alpha band (Figure 4.3-8) and FC5 and FC6 for the theta band (Figure 4.3-9).

A paired t-test was used to examine the average isovist values of clustering coefficient and visual control between the two conditions across participants. Clustering coefficient values are significantly lower (mean = 0.69, SEM = 0.013), for the trials that exhibited a decrease in alpha power (ERD) at the right parietal electrode (P8), compared to the trials (mean = 0.73, SEM = 0.014) that exhibited an increase (ERS) [ $t(19) = -2.17$ ,  $p = 0.043$ ]. There is no significant difference between the two conditions of alpha decrease (ERD) and alpha increase (ERS) at the P8 channel for the values of visual control [ $t(19) = 0.58$ ,  $p=0.57$ ]. For the left parietal channel, however, differences in the mean values of clustering coefficient and visual control between trials with alpha ERD (mean = 0.69, SEM = 0.013; mean = 1.30, SEM = 0.042, respectively) and alpha ERS (mean = 0.72, SEM = 0.014; mean = 1.26, SEM = 0.042, respectively) do not reach statistical significance [ $t(19) = -1.60$ ,  $p = 0.13$ ;  $t(8) = 0.90$ ,  $p = 0.38$ , respectively].

## Alpha Power (8-12 Hz)

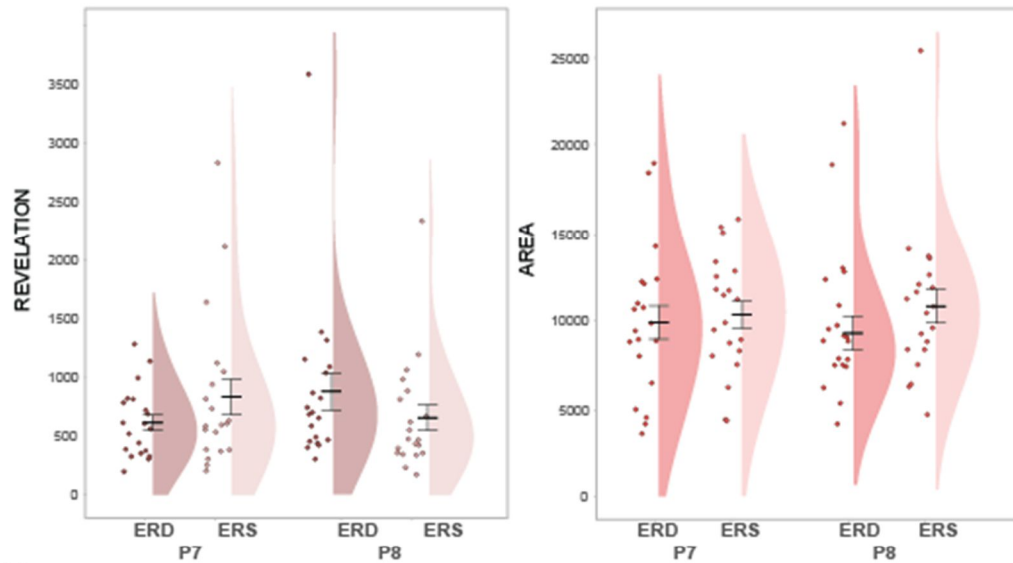
*Hspaciousness*

Figure 4.3-8. Mean isovist values for alpha-decrease and alpha-increase conditions based on the EEG power difference at each individual parietal channel P7, P8. \*  $p < 0.05$ ,

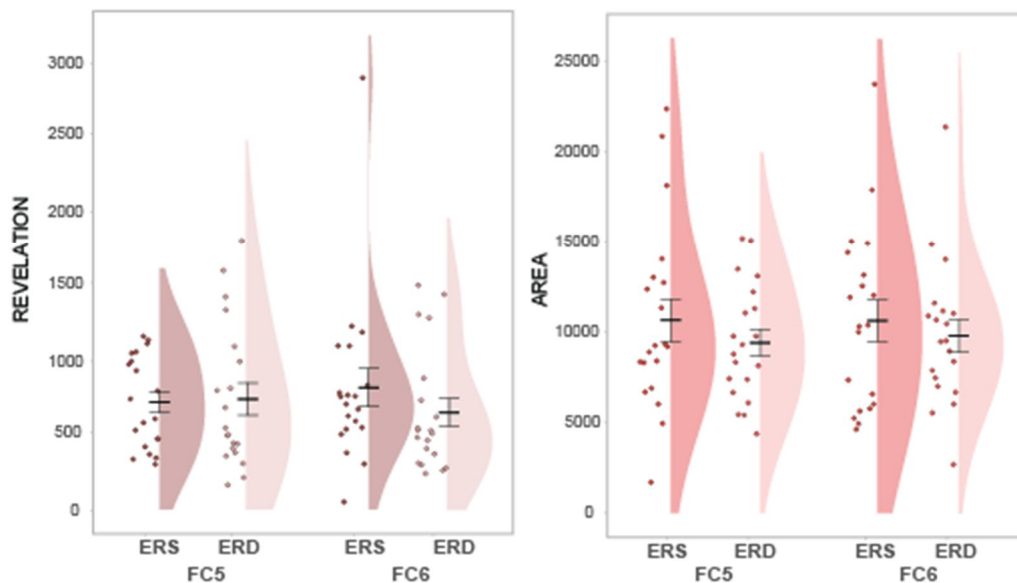
However, examining the change in power at the right frontocentral channel reveals that both isovist properties of clustering coefficient and visual control have significantly different values [ $t(19) = -2.63$ ,  $p = 0.017$ ;  $t(19) = 2.26$ ,  $p = 0.036$ , respectively]. Values of clustering coefficient are significantly lower (mean=0.68, SEM=0.015) and values of visual control are significantly higher (mean=1.33, SEM=0.04) for the trials where participants exhibited an increase in mean theta power (ERS) at the right frontocentral channel (FC6) compared to the cases where there was a decrease (ERD) in theta power (Clustering Coefficient: mean = 0.73,



SEM = 0.01; Visual Control: mean = 1.23, SEM=0.04). In the case of the left frontocentral channel, clustering coefficient has again significantly lower values (mean = 0.69, SEM=0.013) for trials where there was a theta increase (ERS) compared with trials (mean =0.73, SEM=0.011) that exhibited a theta decrease (ERD) [t(19) = -2.14, p = 0.046]. Differences in values of visual control for the theta ERS and theta ERD conditions at the left FC5 channel do not reach statistical significance.

#### Theta Power (4-8Hz)

##### *Hspaciousness*



##### *Hcomplexity*

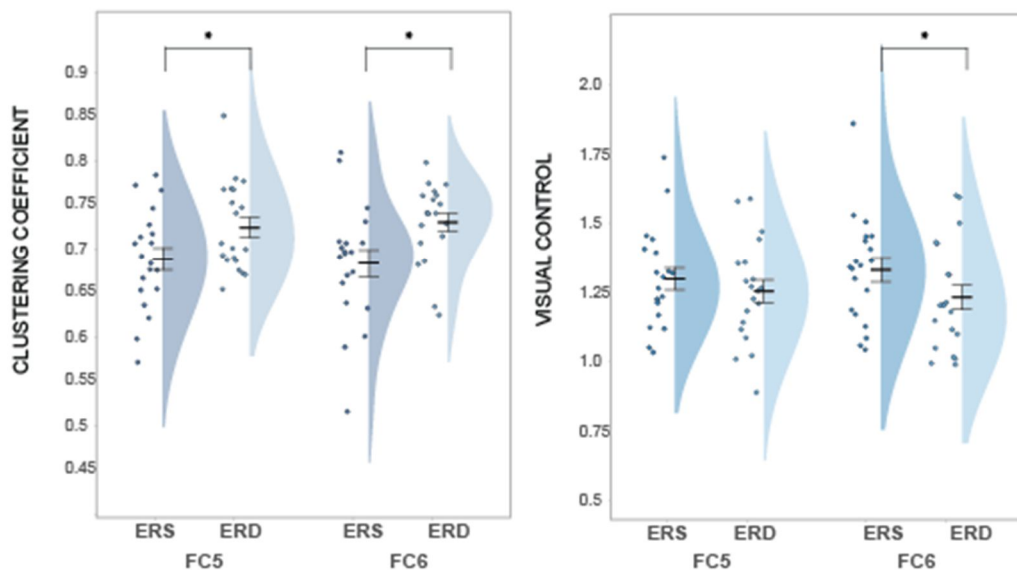


Figure 4.3-9. Mean isovist values for theta-increase and theta-decrease conditions based on the EEG power difference at each individual frontocentral channel FC5, FC6. \* p < 0.05

The response-related analysis, focused on the change in EEG power at each individual channel, suggests that cognitive processes that emerge 3s before the decision to give a response (button-release) are associated with stronger activity in the right hemisphere, which is often observed during navigation. Also, visual control seems to contribute to the processes that are associated to the increase in theta activity even though this is only observed at the right electrode.

The results show that there is no strong association between the isovist properties of revelation and area and the brain dynamics of interest. Therefore, they do not support hypothesis one (*Hspaciousness*), which suggests that a change in the amount of visual information may engender this pattern of brain dynamics. On the other hand, clustering coefficient and visual control seem to contribute to the EEG dynamics that -based on the literature- are assumed to be related to the spatial Aha! experience. Clustering coefficient is significantly lower for the test condition (alpha decrease/ theta increase) for both frequency bands and visual control is significantly higher for the theta-increase condition at the right frontocentral channel.

### **The binary logistic regression model**

The binary logistic regression analysis is used here to explore the predictive power of clustering coefficient on the occurrence of the alpha parietal decrease (Model 1a) and the theta frontocentral increase (Model 2a). Table 4.3-7 shows the contribution of clustering coefficient to Model 1a as being statistically significant ( $p = 0.007$ ). The model calculates the probability of a trial resulting in parietal alpha decrease and clustering coefficient classifies as a single predictor 56.7 % of the cases compared to 51.7% in the null model. The model's chi-square is significant ( $\chi^2 = 7.6$ ,  $df = 1$ ,  $p = 0.006$ ). But the model explains roughly only 5% of the variance. This is not surprising since a lot of other factors may influence this response.

What is of interest here, is the sort of relation that the model suggests between the decrease vs. increase in mean alpha parietal power and clustering coefficient. The odd ration [ $\exp(\beta_{cc}) = 0.076$ ] indicates the proportional change in odds for the occurrence of the event of interest with a change of 1 unit in the continuous variable. However, because clustering coefficient has values from 0 to 1, it makes more sense

to calculate the odd ration for 0.1 unit of change. That is finding the exponential of the  $b$  coefficient multiplied by 0.1<sup>32</sup>,  $\exp(0.1 \times \beta_{cc}) = 0.77$ . The binary regression model (Model 1a) shows that with 0.1 unit of increase in clustering coefficient it is almost 25% less likely for the parietal alpha decrease to occur.

Event of interest (Y): <i>Parietal Alpha power decrease</i>  versus <i>Parietal Alpha power increase</i>		Model 1a				
		Contribution of Spatial variables				
		Logistic Coeff. $b$	p- value	Exponent of coeff. $\exp(b)$	95% C.I for exp ( $b$ )	
Explanatory variables(Xs)	Constant	1.909	0.006	6.745		
	Clustering Coefficient	-2.582	0.007	0.076	0.012	0.495
Deviance (-2 x log-likelihood)		274 $\chi^2 = 7.6$ , df = 1, p = 0.006				
Nagelkerke R2		5%				
Hosmer-Lemeshow Goodness of fit		p = 0.55				
Classification Accuracy		56.70% (Null model 51.70%)				

Table 4.3-7. Binary regression model for alpha parietal decrease (Model 1a).

Event of interest (Y): <i>Frontocentral Theta power increase</i>  versus <i>Frontocentral Theta power decrease</i>		Model 2a				
		Contribution of Spatial variables				
		Logistic Coeff. $b$	p- value	Exponent of coeff. $\exp(b)$	95% C.I for exp ( $b$ )	
Explanatory variables(Xs)	Constant	1.7	0.012	5.474		
	Clustering Coefficient	-2.255	0.014	0.105	0.017	0.635
Deviance (-2 x log-likelihood)		298 $\chi^2 = 6.25$ , df = 1, p = 0.012				
Nagelkerke R2		4%				
Hosmer-Lemeshow Goodness of fit		p = 0.67				
Classification Accuracy		58.20% (Null model 51.80%)				

Table 4.3-8. Binary regression model for theta frontocentral increase (Model 2a).

Model 2a ( $\chi^2 = 6.25$ , df = 1, p = 0.012) describes the contribution of the variable of clustering coefficient in the calculation of the probability of a trial resulting in an increase in frontocentral mean theta power (Table 4.3-8). The model again explains roughly 4% of the variation in the outcome and classifies correctly 58.2% of the cases in comparison to the null model that has a 51.8 %. Clustering coefficient is again a significant variable (p = 0.014) and the model suggest that as the variable increases by 0.1 unit it is 20% less likely for the frontocentral theta increase to occur [ $\exp(0.1 \times \beta_{cc}) = 0.80$ ]. In the next section, the contribution of other non-spatial

<sup>32</sup> <https://onlinecourses.science.psu.edu/stat462/node/207/>

factors is also discussed, for both the alpha response and theta response models, which seems to improve the fit of the models and the percentage of correct classification of cases.

#### **4.4 Contribution of Non-geometric Factors**

Besides the spatial factors, there are of course several other variables that may be related to the spatial Aha! experience. This section discusses other non-geometric factors (age, spatial abilities, presence of landmarks, etc.) that may contribute to the feeling of self-localisation and the decision to release the movement button to respond to the task. Although the focus of the thesis is on the spatial properties that engender the Aha! moment, these other factors may facilitate or hinder the representational change or place recognition. Individual properties and the presence, or absence, of landmarks, for example, may have an effect on the processes that are related to re-orientation, such as attention monitoring, decision making, and conflict resolution or the evaluation of the environmental stimulus. The influence of other factors on the expected brain dynamics (i.e. alpha power decrease and theta increase) may also provide further evidence regarding the assumed underlying cognitive processes for each case. This, in turn, may facilitate a better assessment of the role of clustering coefficient and visual control, which – based on the results of the previous analyses – appear to have a stronger association with the spatial Aha! experience. The analysis that follows permits the evaluation of the results within a larger context that includes individual differences, before drawing any final conclusions.

##### **4.4.1 Landmarks**

The spatial pattern of the exploratory behaviour of participants suggests that the presence of landmarks seems somehow to attract button-release responses, as illustrated in Figure 4.2-4. However, it is not clear if, and to what extent, these non-geometric cues actually contribute to the Aha! experience of re-orientation. Roughly in 40% of the trials, at least one landmark was seen during the second half of the trial just before the button-release moment (Figure 4.4-1). However, participants do not appear to rely on the presence of landmarks to give their response since the percentage of trials where a landmark was seen 3s or 6s before the response is quite low (6% and 4% respectively).

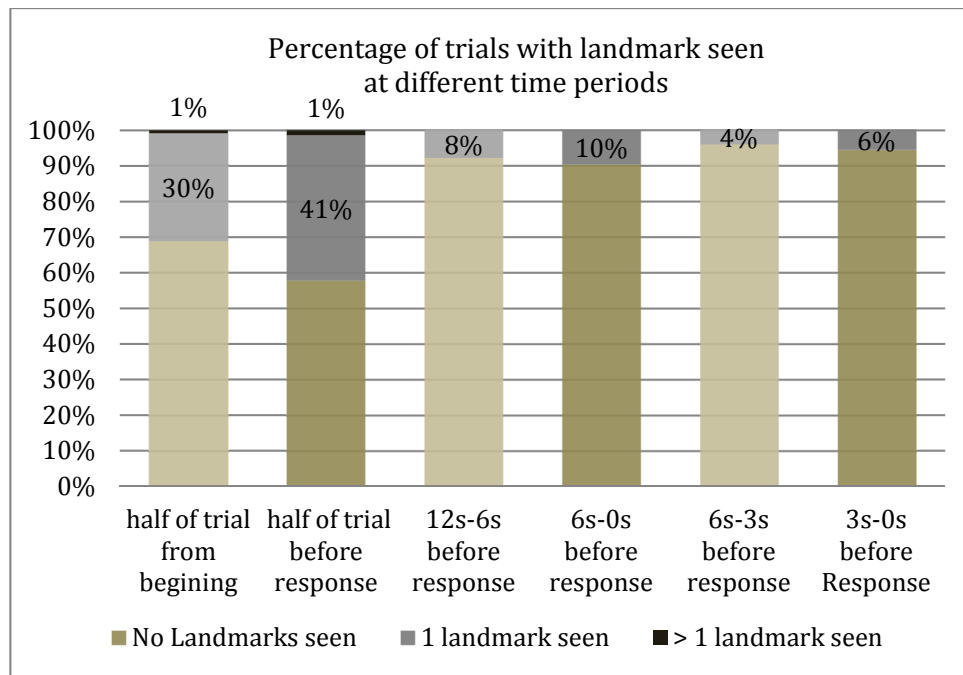


Figure 4.4-1. Percentage of trials with landmark(s) seen at different time periods

The presence of landmarks in each individual route ( $N=260$ ), does not appear to have a great influence on participants' behaviour and performance. A paired t-test was used to compare mean duration, distance travelled, and reaction time<sup>33</sup>, in trials where participants saw a landmark and in trials where no landmark was seen. Trials where participants saw a landmark(s) (mean = 98.40s , SEM =7.86) do not differ significantly [ $t(19) = 0.183$ ,  $p = 0.86$ ] in duration compared to trials where no landmark was seen (mean = 96.69s , SEM = 11.62) as illustrated in Figure 4.4-2. Similarly, mean distance travelled was not significantly different [ $t(19) = 0.88$ ,  $p = 0.39$ ] for trials where a landmark was seen (mean = 489.27m , SEM = 35.76) compared with trials where no landmark was seen (mean = 441.59m , SEM = 51.52). Participants spent on average less time paused, at the location where they gave their response, in trials where a landmark was seen (mean = 4.80s , SEM =0.57) compared to the cases where no landmark was seen (mean = 7.62s , SEM =1.12) and this difference in mean reaction time was found to be significant [ $t(19) = -2.28$ ,  $p = 0.03$ ]. This might reflect that their decision to press the spacebar and give a response was facilitated by the presence of landmarks (Figure 4.4-2). However, the percentage of correct, incorrect and no final response categories for the trials where a landmark

<sup>33</sup> Reaction times refer to the time interval between the button-release moment and the moment participants pressed the spacebar to rotate the map and give their response to the task.

was seen, does not differ significantly from the expected distribution (60%, 25%, and 15% respectively;  $\chi^2=1.63$ ,  $df=2$ ,  $p=0.44$ ).

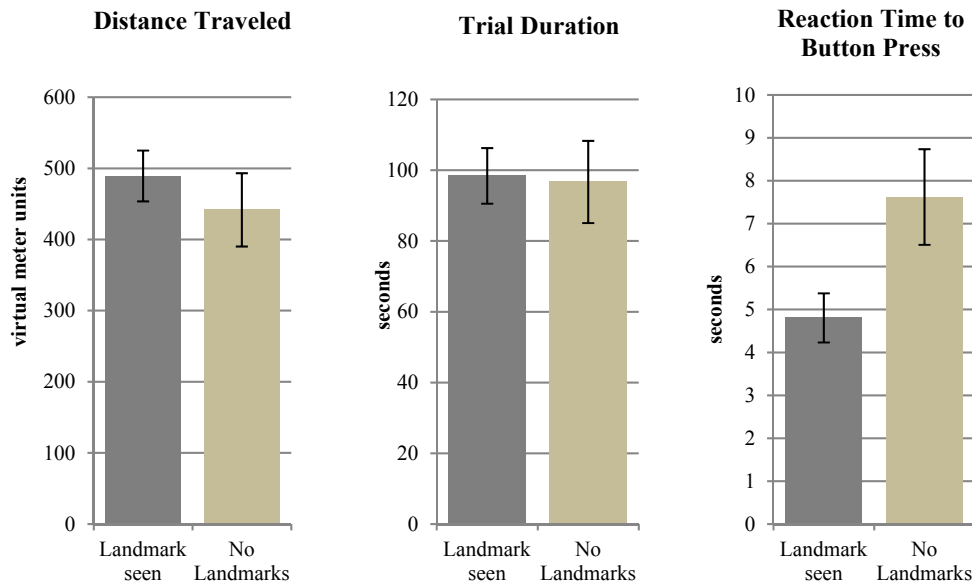


Figure 4.4-2. Bar charts of trial-duration, distance travelled and reaction time for Landmark-seen and No-landmark-seen categories.

To examine further whether the presence of landmarks has an effect on the spatial Aha! experience, I have also analysed the EEG power during the 3s period before the response for the two conditions (Landmark-seen and No-landmark-seen). The literature suggests that possible differences in EEG power between these two conditions will be most likely present at the right frontocentral electrode (Weidemann et al, 2009) and the left parietal channels (Sharma et al, 2017) and that Landmark-seen condition is expected to elicit a decrease in theta power. Thus, I focused the analysis on the theta frequency band during the time period of 3s before the response at the right frontocentral electrode and the left parietal. However, the chi-square test for independence shows that there is no significant relationship between the landmark binary category (Landmark seen/ no Landmark during the 3s period) and the two cases of theta power (increase / decrease in relation to the 6s-3s period) for neither the FC6 nor the P7 channels ( $\chi^2=0.653$ ,  $df=1$ ,  $p=0.42$ ;  $\chi^2=1.26$ ,  $df=1$ ,  $p=0.26$ , respectively).

#### 4.4.2 Individual Differences

Several factors related to individual differences such as age, spatial abilities, preferred use of different reference frames (Carlson et al, 2010; Meilinger, 2008) may affect the occurrence of the spatial re-orientation alongside the spatial geometric factors. To examine which other factors may contribute to the alpha power decrease and theta increase in addition to the clustering coefficient variable (section 4.3.2), I used again the binary regression analysis. These binary regression models predict the expected brain dynamics based on spatial and other individual factors.

Models 1b (Table 4.4-1) predicts alpha power decrease based on the variables of clustering coefficient and age. Age is considered as an important variable since it is associated with significant differences in the amplitude and latency of the P3 component and older adults tend to show a decline in spatial navigation skills. The binary regression model (Model 1a; Table 4.3-7) showed that with 0.1 unit of increase in clustering coefficient it is almost 25% less likely ( $\exp(0.1 \times b_{cc}) = 0.76$ ) for a decrease in parietal mean alpha power to occur. It can successfully classify, as a single predictor, 56.7 % of the cases, compared to 51.7% in the null model.

The age variable, as an additional predictor, improves significantly the binary regression model (block  $\chi^2 = 8.41$ ,  $df = 1$ ,  $p = 0.004$ ). Model 1b (Table 4.4-1) explains roughly 10% of the variation in the outcome (Nagelkerke  $R^2$ ) and classifies correctly 59.6% of the cases. The age variable has a significant contribution to the prediction of the outcome ( $p=0.005$ ). The exponentiated coefficient ( $\exp(b_{age})=0.91$ ) reveals that as age increases by one year while keeping the clustering coefficient constant, it is almost 10% less likely for an individual to exhibit this brain response. And with 0.1 units increase in clustering coefficient, it is roughly 20% less likely to have a decrease in parietal alpha power ( $\exp(0.1 \times b_{cc}) = 0.79$ ).

Event of interest (Y): <i>Parietal Alpha power decrease</i>  versus <i>Parietal Alpha power increase</i>		Model 1b				
		Contribution of Spatial & non-spatial variables				
		<i>Logistic Coeff. b</i>	p- value	Exponent of coeff. exp(b)	95% C.I for exp (b)	
Lower	Upper					
Explanatory variables(Xs)	Constant	4.892	<0.001	133.22		
	Clustering Coefficient	-2.385	0.017	0.92	0.013    0.656	
	Age	-0.093	0.005	0.911	0.853    0.973	
Deviance (-2 x log-likelihood)		265	$\chi^2 = 16$ , df = 2, p < 0.001			
Nagelkerke R2		10%				
Hosmer-Lemeshow Goodness of fit		p=0.27				
Classification Accuracy		59.60%	(Null model 51.70%)			

Table 4.4-1. Binary regression model for alpha parietal decrease (Model 1b).

Figure 4.4-4 shows this relationship between age and predicted probability, whereas Figure 4.4-3 illustrates the relation of clustering coefficient and the predicted probability for different age groups, as calculated by the model. The figures show a strong correlation between age and the probability of exhibiting a decrease in alpha power according to the model (Figure 4.4-4). Younger individuals are much more likely to exhibit this response. The range of predicted probabilities in a 43-year-old is completely non-overlapping with that of a 20-year-old, although in both cases as clustering coefficient values decrease, the probability of having this brain response increases, as the model predicts (Figure 4.4-3). To clarify, these figures as well as Figure 4.4-5, do not illustrate the actual data but the prediction made by the model based on the available data, that is the values of these variables in the two conditions of alpha power decrease and alpha power increase.

The frontocentral theta response might be associated with recognition-related decision making and therefore differences in spatial abilities may affect this response. Participants who have a low score at the Santa Barbara Sense of Direction test (self-assessed as having a weak sense of direction) will most likely have difficulties in deciding where they are in relation to the map, which might be associated with differences in frontocentral theta power (increase attentional and working memory demands).



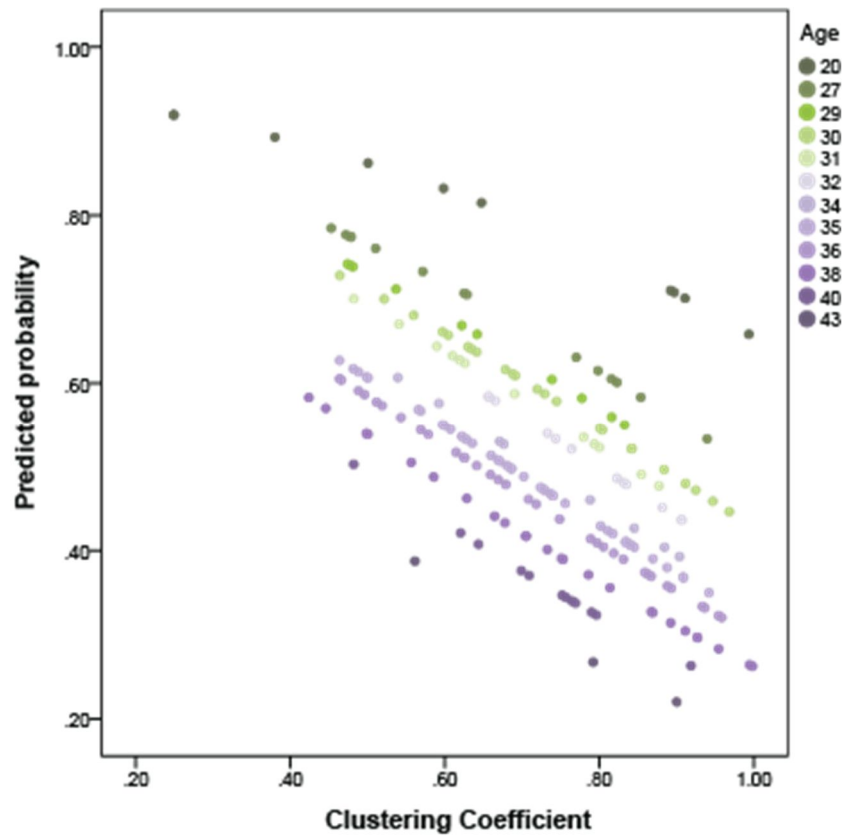


Figure 4.4-3. Predicted probability of parietal alpha decrease as a function of clustering coefficient for different ages.

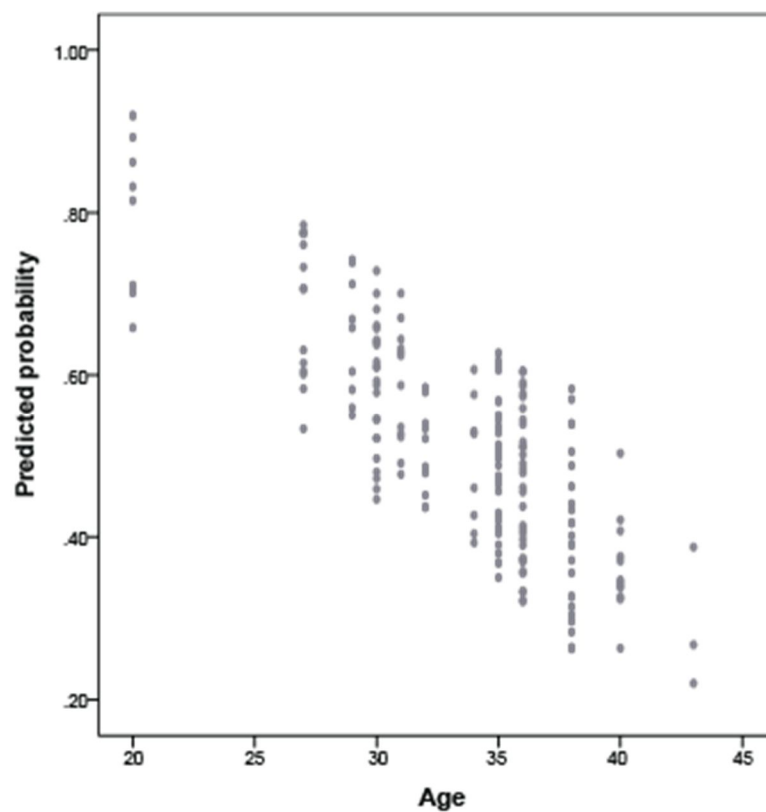


Figure 4.4-4. Predicted-probability of parietal alpha decrease as a function of age.

Model 2b (Table 4.4-2) predicts the occurrence of a frontocentral theta power increase based on clustering coefficient and participants' score in the Santa Barbara Sense of Direction test (SBSOD). The variable is included in the model as a categorical predictor. Participants are assigned into 3 groups based on their score in the test. The Low Score group included cases where the test score was below 4, the Medium Score between 4 and 5 (median score=4.5), and the High Score included individuals that scored above 5. The baseline category for the model is the High Score category.

Event of interest (Y): <i>Frontocentral Theta power increase</i>			Model 2b				
			Contribution of Spatial & non-spatial variables				
versus <i>Frontocentral Theta power decrease</i>			<i>Logistic Coeff. b</i>	p- value	Exponent of coeff. exp( <i>b</i> )	95% C.I for exp ( <i>b</i> )	
						Lower	Upper
Explanatory variables	Constant		1.565	0.33	4.782		
	Clustering Coefficient		-2.483	0.009	0.083	0.013	0.54
	Santa Barbara Score		0.003				
	* High as	Low	0.995	0.003	2.705	1.401	5.224
	Reference	Medium	-0.092	0.792	0.912	0.462	1.803
Deviance (-2 x log-likelihood)			286 $\chi^2 = 18.3$ , df = 3, p < 0.001				
Nagelkerke R2			11%				
Hosmer-Lemeshow Goodness of fit			p=0.108				
Classification Accuracy			63.60% (Null model 51.80%)				

Table 4.4-2. Binary regression model for theta frontocentral increase (Model 2b).

The Santa Barbara sense of direction score in Model 2b appears to be a statistically significant variable in the binary regression model that predicts the frontocentral theta response (Table 4.4-2). The initial model (Model 2a, Table 4.3-8) which includes only the spatial variable, classifies correctly almost 58.2% of the cases, although the Nagelkerke's  $R^2$  suggests that the model explains roughly only 4% of the variation in the outcome. The percentage of correct classification increases to 63.6%, by adding the variable that shows the subjective evaluation of the sense of direction. This addition leads to a statistically significant improvement of the model (block  $\chi^2 = 12.1$ , df = 2, p = 0.002) and the model now explains 11% of the variation in the outcome. The model shows that the contribution of the categorical predictor of the Santa Barbara Score is significant (p=0.003) and that the Low score category is almost 3 times more likely to elicit an increase in frontocentral theta power in relation to the reference category of High Score, as shown in Figure 4.4-5. Again, this figure illustrates the probabilities as predicted by the model based on the data,

the range of values of each predictor in each of the two conditions. Clustering coefficient now shows that with a 0.1 increase it is roughly 20% less likely for a participant to exhibit an increase in theta power at frontocentral channels ( $\exp(0.1 \times b_{cc}) = 0.78$ ). This suggests that the increase in mean theta power, observed 3s before participants enter their final location, is influenced by participants' confidence regarding their sense of direction and their ability to orient during navigation.

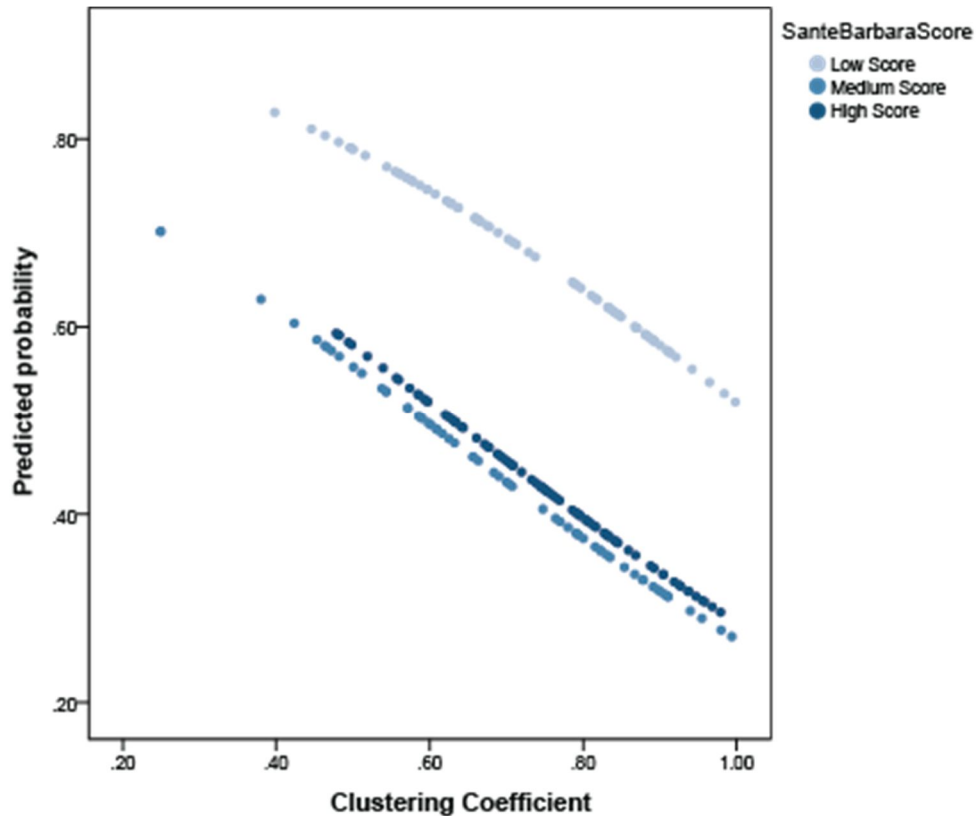


Figure 4.4-5. Predicted probability of frontocentral theta increase as a function of clustering coefficient for low, medium and high sense of direction scores.

The two binary logistic regression models, Model 1b and Model 2b, include the spatial factor and the non-spatial variables of age and Santa Barbara Score respectively, and thus they give a better sense of the underlying mechanisms of the brain dynamics assumed to be related to the spatial Aha! experience of re-orientation. It is far beyond the aim of the thesis to build a statistical model that explains the alpha and theta responses. The results discussed here do not suggest that we can predict with certainty the occurrence of these brain dynamics based only on the values of the predictors. For example, although Hosmer & Lemeshow's test

suggests that the models are a good fit for the data, the models explain only 10% of the variation. This analysis offers an opportunity to examine the relation between the independent variables and the brain's response. Studying the contribution of other factors on the alpha and theta response can help assess the relation of these responses to the possible cognitive processes they reflect.

For example, the estimated probability of the occurrence of a parietal alpha decrease appears to decrease as age increases. This effect of age is similar to the effect of aging on the P3 component leading to a decrease in amplitude and increase in latency (Polich, 2012). Thus, the effect of the age factor on the occurrence of parietal alpha decrease allows us to speculate that it is possible that this response is related to memory-related operations that may lead to an update or a switch of the representation. The contribution of the Santa Barbara score variable in predicting whether trials will exhibit a frontocentral theta increase, suggests that it is likely that this brain response reflects processes that are related to decision making and increase task demands. Other variables that may reflect individual differences, such as familiarity with the videogame environment, a background discipline related to spatial problem solving (e.g. architects) vs. no related discipline or gender, do not appear to have a statistically significant effect as predictors in none of the models. Similarly, distance travelled during the trial, duration of the trial or trial's number cannot predict the occurrence of alpha power decrease nor the increase in frontocentral theta.

## **CHAPTER 5      Discussion and Conclusions**

## 5.1 Introduction

The working hypothesis that forms the basis of this thesis is that the moment of spatial re-orientation can be seen as an instance of the greater concept, or phenomenon, that we call the Aha! moment. The literature review includes discussions on the notion of the Aha! moment in insightful thinking (section 2.1) and the spatial experience of wayfinding (section 2.2) and comments, when relevant, on their ‘common junctions’. Koestler’s (1964) ‘chronological matrices’ (section 2.1.1) are a good example which perhaps facilitates the conceptualisation of the analogy suggested by the working hypothesis. His description refers to matrices that go beyond the representations of separate episodic memories (as “linear chains of events”). These representations combine and integrate (or ‘bisociated’) “multi-dimensional structures in semantic space”, hinged at points of reference which are often “indifferent to temporal order” (ibid.). This relationship seems analogous to theories in cognitive neuroscience that attempt to explain the transformation of egocentric to allocentric representation or higher-order structures of spatial relations.

Departing from this analogy, the aim of this experimental paradigm was to assess what sort of spatial properties contribute to the emergence of the Aha! moment of spatial re-orientation. This chapter discusses the main findings and possible directions for future research. Both behavioural (section 4.2) and EEG (section 4.3) results suggest that the factor of complexity, compared to the factor of spaciousness (amount of visual information), appears to be a stronger predictor of the spatial Aha! moment. To better understand the factor of complexity and how the two associated isovist properties (i.e. clustering coefficient and visual control) contribute to the Aha! experience of spatial re-orientation, the chapter also explores the different processes that are possibly reflected by the relevant pattern of brain dynamics (posterior alpha decrease and a frontal theta increase). The chapter continues with some reflections and theoretical speculations on how these locations which appear to engender the spatial Aha! moment could be related to the emergence of higher-order knowledge structures. The last section summarises the main conclusions and contributions of this thesis. Hopefully, the discussion and conclusions that follow will extend to some degree our knowledge regarding the Aha! experience.

## 5.2 Key Findings and Future Research Directions

The thesis examines the moment that participants have the Aha! experience of re-orientation, a transition from a state of being lost and disorientated to a state of being able to situate and orient themselves in relation to the map of the virtual environment. This moment has two key underlying mechanisms: the recovery of a spatial frame of reference (context/place recognition and self-localisation) and the heading determination. The focus here is on the aspect of self-localisation and context/place recognition rather than the sub-process of heading retrieval. As stated in the introduction and section 2.3.3, two main psychologically-relevant spatial factors affect our relation to the spatial layout, namely spaciousness, and complexity, which can be described in terms of two different sets of isovist properties: area/revelation and clustering coefficient/visual control.

The first part of the discussion of both the behavioural and EEG results is focused on the changes in the isovist values of interest in the time preceding a button-release just before participants' response. The objective is to examine which set of isovist properties (Hspaciousness or Hcomplexity) drives the moment of spatial re-orientation and in which cases sudden changes of the relevant isovist values are associated with changes in the EEG data. The second part examines the isovist properties at the exact location where participants gave their response, and, whether the expected brain dynamics of parietal alpha decrease and frontocentral theta increase (which, based on relevant studies, are assumed to be related to the Aha! experience), correlate with a specific set of isovist properties.

Although participants' response accuracy is associated with the heading retrieval process, it was briefly examined in order to confirm that subjects were engaged with the experimental task and able to perform the task with a ratio of correct responses above chance level. Also, their confidence ratings regarding their performance reflected the magnitude of their angular errors. Cases where participants reported certainty regarding their final response fall within the category of correct responses (mean angular error <30 degrees) as opposed to cases where participants thought they were 'probably right' or 'uncertain'.

The peak values of the isovist properties of interest were studied during specific time periods of 3s duration each and in relation to their distance in time from the moment participants released the button of movement just before their response to the task. Because participants' speed was not controlled during the experiment, the peaks in isovist values were also studied in relation to the distance travelled: that is for four segments of equal length of distance travelled (15m) until the button-release moment. The results reveal that peak isovist values averaged across participant for each segment, during the time period and distance-segment closer to the response, have significantly higher mean maximum values of area and visual control, and lower minimum values of clustering coefficient compared to the segment just before that, while there are no significant differences in the values of revelation between these two conditions. In addition, a similar pattern can be observed through visual inspection of the isovist values unfolded both in relation to time (Figure 4.1 9) and distance (Figure 4 10) along the trials of a single participant. Hence, these significant differences in peak isovist values are not produced by variations in speed or in stationary behaviour because the same results are obtained for both time-based (Figure 4.1 11) and distance-based (Figure 5.1 1) analyses.

The analysis of the two distinct time-windows of 3s duration each, preceding the button-release moment allows us, therefore, to reject the null hypothesis. Participants tend to give their response to the orientation task after passing through locations with higher area, higher visual control and lower clustering coefficient. These spatial properties most likely act as environmental cues and contribute, at a greater degree, to the moment of spatial for re-orientation. The stimulus-related EEG analysis is focused again on these peak values just before the button-release moment, and reveals in which of these cases the transition in the perceived visuospatial information is associated with changes in the EEG power.

The mean EEG delta/theta power difference, averaged over both frontocentral channels, shows a significant increase only in the cases where there is a large negative peak in the values of clustering coefficient and a decrease when the peak change is small (Figure 4.3-3). Large negative peak changes of clustering coefficient



values (above the median of the absolute values) are also associated with increases at the right frontocentral delta/theta power. This is consistent with research on navigation showing greater activity at the right hemisphere and studies showing theta increases at right frontocentral channels during encoding. The three-second epochs that are time-locked to small changes in the values of clustering coefficient and area show a decrease in mean delta/theta power at left frontocentral channels (Figure 4.3-4). However, the mean EEG power at the left frontocentral electrode is almost equal to the mean EEG power during a 3s period before that (baseline) when examining the cases that are time-locked to large peak changes in area and clustering coefficient. Perhaps this suggests that large peak changes in these cases do not reflect an increase in spatial processing. These results, therefore, show that increased processing of the perceived visuospatial information has a stronger association with location that are characterised by sudden and large decreases in the values of clustering coefficient.

The response-related analysis is focused at the isovist values of the location where participants gave their response and the brain dynamics related to the button-release moment. The frequency distribution analysis of the isovist measurements at these locations were examined in relation to a) the population of values at all the locations of each route travelled during each trial (Figure 4.2-15) and b) the population of all points of the whole system highlight the main tendencies (Figure 4.2-16 and Figure 4.2-17). The measurement of revelation does not present any clear tendencies while button presses are concentrated in higher percentiles of isovist area in relation to the whole route but, not in relation to the whole system. This means that participants tend to move towards open square, for instance, but they do not depend on the biggest squares of the whole environment in order to get 'a sense' of their orientation. However, the trends of the isovist properties related to the factor of complexity present a very clear image, both in relation to the route travelled and to the whole environment. Participants choose to give their response to the orientation task at locations within the highest range of values of visual control and lowest range of clustering coefficient.

The ANOVA found significant differences in mean isovist values at these locations between trials that exhibited a parietal alpha decrease versus increase or a

frontocentral theta increase versus decrease (at the four channels of interest, two parietal and two frontocentral, respectively), but only for the cases of clustering coefficient and visual control (Figure 4.3-7). No significant difference was found in area and revelation. Clustering coefficient is significantly lower for trials with an alpha decrease at the right parietal channels (Figure 4.3-8) and trials that exhibited a theta increase at either frontocentral channels just before the button-release moments (Figure 4.3-9). Visual control values are significantly higher for the theta-increase condition at the right frontocentral channel. These results suggest that cognitive processes associated with the decision to give a response (button-release) are associated with stronger activity in the right hemisphere, which is often observed during navigation. But most importantly, these findings suggest that the isovist properties of revelation and area do not have a strong link with the expected brain dynamics since their values do not exhibit significant differences between the two conditions. Hence, these findings do not support hypothesis one (*Hspaciousness*) which suggests that a change in the amount of visual information may engender this pattern of brain dynamics but rather reveal that hypothesis two (*Hcomplexity*) is more likely to be the case; that is, the expected pattern of brain activity can be triggered by a change in the complexity of the visual information.

The binary logistic regression model confirms that clustering coefficient at the button-release location is a significant spatial predictor of the expected brain dynamics: the alpha decrease at both parietal electrodes and the theta increase at both frontocentral channels. In other words, with a 0.1 increase in the isovist values it is roughly 20% less likely for a participant to exhibit these brain responses. It also shows that for constant values of clustering coefficient, the estimated probability of the occurrence of a parietal alpha decrease appears to decrease (10% less likely) as age increases 1 year (Figure 4.4-3) and that participants who have a low score at the Santa Barbara Sense of Direction test (below 4/7) are 3 times more likely to elicit an increase in frontocentral theta power in relation to participants who had a high score (Figure 4.4-5). The contribution of the Santa Barbara score variable, in predicting whether trials will exhibit a frontocentral theta increase, suggests that it is likely that this brain response reflects processes that are related to decision-making and reflect increase task demands. These appear to be more pronounced when participants'

confidence regarding their sense of direction and ability to orient during navigation is relatively low.

In summary, the behavioural analysis shows that the properties of clustering coefficient, visual control and area have an effect on participants' exploratory behaviour. They appear to drive participants' responses since mean peak values of these properties are significantly different between the time-period (or distance-segment) closer to the response and the period just before that. Revelation shows no significant differences. However, the EEG analysis – focusing on the brain's response to these peak changes in isovist values – shows a stronger association between sudden changes in the values of the clustering coefficient property and changes in mean EEG power. A significant increase in frontocentral delta/theta power, most likely reflecting increase spatial processing, is evident only when participants encounter large peak changes (negative drops) in the values of clustering coefficient, just before the button-release. This finding rather implies that these transitions in the values of clustering coefficient may act as environmental cues and contribute at a greater degree to spatial re-orientation.

The response related analysis suggests that responses to the re-orientation task are more likely to occur at locations that have clustering coefficient values which fall within the lowest range of the whole environment and visual control values which fall within the highest range. The EEG analysis confirms this observation: trials that exhibit the expected response-related brain activity (averaged for each participant for the two conditions for all four channels) have on average even lower values of clustering coefficient and significantly higher values of visual control compared to the control condition (alpha increase/theta decrease). The isovist properties that describe the *Hspaciousness* have no significant differences.

Consequently, the results here illustrate that the 'complexity' factor is more likely to trigger the Aha! moment of re-orientation. The properties of clustering coefficient and visual control capture spatial qualities that seem to be closely related to 'exploration' and 'understanding' (as discussed in section 2.3.3) and appear to be more influential during wayfinding. Clustering coefficient is related to how visual information varies within an environment and the complexity of the environmental

shape. Low values of clustering coefficient occur at a location that promise gaining new visual information (Turner et al., 2001), a quality that is relevant to 'mystery'. And a visually dominant location permits one to get 'a sense' of the distinct local environmental shape probably linked to the psychologically-relevant spatial factors of 'understanding' and 'coherence'.

### **Alternative Hypothesis**

An alternative hypothesis that could be raised here is that both spatial situations – a change in spaciousness and a change in complexity- may contribute, to some degree, to spatial re-orientation but the effects of clustering coefficient and visual control are greater. The rationale that supports this alternative hypothesis is that when approaching a typical street junction there is a sequence of events taking place: first, a sudden increase in revelation coupled with an increase in area when entering the junction, and then, after a certain time-interval once one is at the centre of the junction there is a reduction in clustering coefficient and an increase in visual control. This explanation suggests that there is a specific lag between these two events, that is the high values of area and revelation at the threshold of the junction and the low clustering coefficient values, and the high values of visual control at the centre of the junction. Below is an examination of this possibility and a discussion of the data of this thesis in relation to the possible scale of this temporal lag.

If this temporal lag is greater than 3 seconds then the values of revelation and area would be significantly higher during the 6s-3s period compared with the 3s-0s period, which, given the data of the thesis (Figure 4.2-11) is not the case. One possibility is that this is due to variations in speed sampling. If we consider this lag between the events in terms of distance (Figure 4.2-12), there is again no evidence to support this explanation. A second possibility is that this temporal lag is less than 3 seconds. Although the values of revelation do not have significant differences between the different time-periods of interest (Figure 4.2-11) or distance segments (Figure 4.2-12) and the EEG analysis (Figure 4.3-3 and Figure 4.3-7) does not present any evidence of the involvement of revelation in the Aha! moment, the case of isovist area is a bit more complex.

Firstly, there is a high correlation between the properties of area and visual control (isovist area is used in the calculation of the visual control property) which makes the distinction between the contribution of each factor more complicated. Secondly, area is significantly higher during the 3s-0s period compared with the 6s-3s period (Figure 4.2-13). This means that it might somehow contribute to the event of interest in driving participants' responses. If the effect of this property – as an environmental cue driving spatial re-orientation – is strong, then one might expect that large peak changes in the amount of the perceived visual information would result in increased spatial processing. The evidence of the EEG stimulus-related analysis does not provide strong support for this explanation, because there was no increase in mean frontocentral delta/theta power. There is, however, a significantly decrease in frontocentral delta/theta power which is associated with small changes in values of isovist area compared to trials with large changes (Figure 4.3-4).

Also, it is possible that the combination between variations in street width and variations in speed results in variability in the scale of this temporal lag, which in some trials might be greater than 3s and in other trials less than 3s. In this case, this would distort the relevant data in the time-period and distance-segment analyses and occlude any evidence supporting this sequential dependency (a change in spaciousness followed by a change in complexity). For example, if this is the case, then the highest peaks in the values of revelation would be divided between the two intervals that are close to the button-release moment (6s-3s and 3s-0s or 30m-15m and 15m-0m) and this would not result in any significant differences between the two periods.

In general, the evidence gathered from this experiment does not provide strong support for this alternative hypothesis. The results show that participants give their response at locations with low values of clustering coefficient and high values of visual control. Trials where participants exhibit a parietal alpha decrease or a frontocentral theta increase just before the button-release moment, are coupled with significantly lower values of clustering coefficient and higher values of visual control, compared with the average values of the urban environments. And there are no differences in the values of area or revelation compared with the average values. However, the complexity of this issue gives rise to new future research directions. It

would be fruitful to investigate this alternative hypothesis in more controlled situations. This would offer the opportunity to examine in depth this sequential dependency and whether the Aha! moment is triggered by this chain of events. Even though the results here suggest that a change in complexity is a necessary condition which triggers the spatial Aha! Moment, there is still a possibility that a change in spaciousness does influence this moment.

Therefore, an interesting direction for future research is a more in-depth study of this sequential dependency and of the relation between the isovist values of clustering coefficient and visual control, and how each property contributes to specific cognitive process during wayfinding. For example, the findings of this thesis suggest that clustering coefficient might be related to context recognition whereas visual control might contribute mainly to stimulus-evaluation processes, more closely related to spatial working memory demands and decision-making. Brain dynamics can be analysed for periods that are time-locked to the moment when participants cross a specific street junction. These street junctions can be designed to have differences in terms of type and shape and thus different values of isovist properties, which will allow to test the sequential dependency of the two events (change in spaciousness followed by a change in complexity). This type of a more controlled experimental design will allow the comparison of brain activity in different experimental conditions that have an immediate relation to the isovist properties. We could additionally assess the contribution of each isovist property to different cognitive processes involved in wayfinding, and re-orientation in familiar and unfamiliar environments as well, by designing controlled tasks that focus exactly on these spatial properties.

### **The contribution of landmarks**

According to the literature, re-orientation depends mainly on geometric factors and environmental shape (Julian et al, 2018). Even though the focus of the thesis is on the effect of such geometric cues during spatial re-orientation, the possible influence of the visually-salient landmark-objects, which are present within the virtual environments, also deserves attention.

The pattern of participants' exploratory behaviour suggests that the presence of landmarks might trigger button press response (Figure 4.2-4). However, the results show that in only a small percentage of the cases was there a landmark seen 6s before the response; and, the percentages of cases where a landmark was seen in the first half of the trial - compared to those where a landmark was seen in the second half - do not exhibit a great difference (Figure 4.4-1). Thus, participants' decision to respond to the task does not appear to be driven by the presence of landmarks. Also, response accuracy was different for the trials where a landmark was seen versus the cases where no landmark was seen. It is therefore reasonable to assume that the geometric aspects of the environment are stronger predictors for both behavioural and brain responses which reflect the moment of re-orientation. However, landmarks seem to contribute to the overall knowledge acquisition process and facilitate the decision-making, as reflected by the decrease in reaction times in trials where a landmark was seen (Figure 4.4-2).

Of course, the only quality that made landmark-buildings distinguishable in the urban environments, was their different texture and colour. The landmark-objects in this paradigm are visually-salient buildings, which can only be perceived at a local level. They cannot be perceived from a distance (which usually facilitates orientation) and the possibility of forming constellations is reduced by the fact that they cannot be perceived simultaneously. Also, even though they differentiate in terms of colour and texture, in relation to the other buildings which are just grey, they all share the same visual attributes and are only slightly different in shape.

The characteristics of their location or their isovists could have had an impact on their contribution to the re-orientation process. Perhaps visual salience alone is not a sufficient condition for a point location to be labelled as a landmark, especially when the visually significant buildings have the same characteristics. The salience of landmarks as discrete objects can be based on the object's visual, semantic or structural properties. The structural salience of landmark-objects, according to Klippel and Winter (2005), is influenced by the conceptual complexity. That is, it depends on whether their location is "cognitively or linguistically easy to conceptualize in route direction" (Klippel & Winter, 2005).

The relation between geometric and non-geometric cues for re-orientation seems to be quite a fruitful field for future research. Apart from the debate that non-geometric cues might contribute to the orientation of already oriented individuals, mainly in familiar environments and not in unfamiliar environments, there is also a debate regarding their contribution to the cognitive process involved during re-orientation. It is still unclear whether non-geometric information contributes directly to the experience of re-orientation or if it operates on “a separate post-reorientation mechanism that checks the features at the target location for consistency with visual memory” (Julian et al, 2018).

Future research can focus on the contribution of non-geometric cues, such as landmark-objects, by comparing cases of visual salience versus structural salience (the spatial properties of their location and their relation to intrinsic environmental axes) to clarify their distinct contribution to spatial knowledge acquisition. The findings of the current experiment suggest that isovist properties are stronger predictors of participants' brain response and behaviour than visually-salient landmarks. Klippel (2010) comments that isovists do not appear “to predict many people’s performance, in tasks where local landmarks may have greater salience than the isovist shape” (Klippel, (2010). This triggers an interesting line of research. The effect of visually salient landmarks on re-orientation can be compared with the effect of landmarks that are not only visually salient but are also bound to navigationally-relevant spatial features (by being situated in locations which are salient due to their environmental shape). This comparison may provide additional evidence of the importance of environmental shape and its relation to the structural salience of landmark-objects.

### **Differences between urban environments**

The data from participants' exploratory behaviour, as shown in Figure 4.2-5, suggest that they spent more time paused in City 1 in relation to City 2 and the duration of pauses during exploration is reduced further in City 3. Although the order of starting locations in each session (virtual city) was randomised, the order of the sessions was the same for all participants. That is, participants first explored City 1 followed by City 2 and City 3. This could be considered a limitation of the thesis, on the one



hand, but as a departure point for future research, on the other hand, since it appears to generate a new hypothesis.

Before the start of the actual experiment, a simple urban environment was used in the beginning to help participants develop familiarity with the task and with virtual navigation within the game environment. However, it is likely that participants still spent some additional time familiarising themselves with the environment and the task, during their exploration of City 1. Thus, the data presented in Figure 4.2-5 suggest that perhaps there was a learning effect taking place which was caused by the fact that the order of the sessions (urban environment) was not randomised. However, it is unlikely that this learning effect involves the acquisition of knowledge regarding the spatial layout, which is the object of investigation, since each city environment is different. The learning effect that took place most likely reflects an increased familiarity with the general elements of the virtual game environment (ambience, surface textures, movement buttons). It is less likely to reflect a type of learning relevant to the orientation task, since there are no significant differences in the percentage of correct responses between the three cities (section 4.2.1).

However, there is a significant difference in the percentage of responses with high confidence rating (equal to 3, reflecting 'certainty') between City 1 and City 2 (section 4.2.1). It is possible that this is caused by an increased familiarity with the task but there are no significant differences in the percentage of responses with high confidence rating between City 1 and City 3. Hence, a reasonable explanation that emerges is that participants felt more certain of their responses in City 2 due to the specific spatial configuration of this environment. One obvious difference between the two urban environments of (Figure 3.5-1) is that City 2 has two distinct grid configurations which might contribute to self-localisation. Of course, a counter-argument to this explanation is that, if that were the case, there should be significant differences between City 2 and City 3. Nevertheless, this observation opens up new directions of research. Future research could focus on examining how the presence of different grids within an urban region (e.g. in terms of scale, orientation and configuration), contributes to the re-orientation process and emergence of the spatial Aha! moment.

### **Mobile brain imaging technology during real-world navigation**

Apart from controlled experimental designs in virtual reality environments, the idea of running reliable exploratory experiments in actual real-world conditions, seems quite plausible now. Synchronized Virtual Reality/EEG systems provide the means of a real-world experience and where different experimental conditions can be designed and compared but does not involve actual movement. On the other hand, using mobile brain imaging technology, such as wireless EEG while subjects perform actual movement within real environment has several challenges. The Emotiv, for example, is not stable with movement and thus wireless electrodes will need to be implemented in a wearable brain cap, while, at the same time, walking produces great movement artifact in the signal. Fortunately, relevant research on whole-body movement artifacts using machine-learning algorithm (ICA) (Gwin et al, 2010) is currently evolving. Research on movement-related artifacts and their identification within the EEG data stream is very promising for future research since it will allow researchers to conduct reliable EEG experiments during real-world navigation. Advances in mobile brain imaging technology (mobile EEG and fNIRS) suggest that this will soon be plausible, and researchers have started exploring the technical challenges and solutions for real-world recording (Park et al, 2018). Future research can, therefore, focus on the spatial behaviour and experience of different environmental settings, without reducing the richness of experiencing the complexity of real-world situations.

## **5.3 General discussion**

### **The Spatial Factor of Complexity**

Local properties of the spatial configuration appear to have a significant contribution to the emergence of the spatial Aha! moment. This is not surprising since local isovist measures can be used to describe the shape and complexity of spaces (Psarra & Grajewski, 2001) and the shape of the surrounding visible space apparently plays a key role in orientation and in spatial learning (Montello, 2007). Although other factors might affect the occurrence of this event, such as individual differences in spatial abilities or in strategies, the local spatial properties that are associated with a change in the complexity of the visual information appear to be strong predictors.

The findings of this thesis suggest that a change in the amount of visual information is not a sufficient condition to provoke the Aha! experience, even if this event might trigger an element of surprise or contribute to other relevant processes that precede this moment (Figure 4.3-4). In contrast, a change in the complexity of the visual information can, perhaps, be considered an environmental novelty that is more closely related to exploratory behaviour. This is supported by the increased delta/theta power at frontocentral channels coupled with a large sudden reduction in the values of clustering coefficient preceding the button-release moment (Figure 4.3-3, Figure 4.3-4). It is a sort of informationally-relevant novelty akin to the task-related, target stimulus in the oddball example, which is associated with the P3b component (as opposed to the novelty P3a).

Values of clustering coefficient that reflect the complexity factor can predict the occurrence of alpha power decrease (as shows the binary regression model in section 4.3.2) which is also related to the P3b subcomponent (Peng et al, 2012). This brain response appears to be relevant to the spatial Aha! moment because it has been reported to reflect processes related to spontaneous backtracking in goal-directed navigation (Javadi et al, 2018) and the translation of spatial information between reference frames (Javadi et al, 2018; Lin et al, 2015). Interestingly, even though the two isovist properties of clustering coefficient and visual control have a strong negative correlation, the mean values of visual control are not significantly higher, for trials that exhibited a parietal alpha decrease.

On the other hand, response-related theta increase might also reflect processes that support the Aha! moment. Theta frontocentral activity might be involved in conflict resolution and the initiation of memory retrieval processes leading to the Aha! effect. Increase theta activity has been related to decision-making during recognition (Jacobs et al, 2006). It has also been observed during critical points of navigation, reflecting increased task demands, and this response was generated in the anterior cingulate cortex (Lin et al, 2015). The involvement of this brain area in insightful problem solving (as discussed in section 2.1.3) is thought to reflect cognitive control and initiation of conflict resolution.

Clustering coefficient values are significantly lower and visual control values are significantly higher for the trials that exhibited an increase in mean theta power at the right frontocentral channel (Figure 4.3-6). The differences observed in the values of these properties (between the two theta-response conditions) might reflect cognitive processes related to conflict resolution and the evaluation of choices for further movement (for the theta-increase condition). This interpretation is aligned with the theory from environmental psychology and the discussion in section Environmental Psychology, Spatial Behaviour and Isovist Properties2.3.3 since the conflict resolution processes might be triggered by the spatial quality of 'understanding' and local 'coherence', which "allows one to predict and orient within the picture plane (the array that is before one)" (Kaplan, 1978).

Consequently, both properties may contribute to the moment of spatial re-orientation, but in different ways. Locations with lower clustering coefficient seem to act as environmental cues, where allocentric representations can be anchored during exploration of unfamiliar environments. Encoding of such key points or cues may trigger memory processes and retrieval/recall of relevant information from a different reference frame resulting in a change in the course of action. Visually dominant locations might facilitate conflict resolution (between old and new representation) and the evaluation of the choices of movement available in the specific location. It is possible that these processes facilitate place/context recognition and the translation of spatial information between reference frames.

### **The Effect of Multi-directionality**

Locations with lower values of clustering coefficient usually have multi-directional fields of view and more complex shapes than, for example, open convex spaces such as urban squares. The complexity of the perceptual input at these locations is usually summed up under their common characteristic of having a 'spiky' isovist. The discussion on environmental psychology theories in section 2.3.3 leads to the assumption that the relationship between the properties of clustering coefficient and visual control might be associated with the spatial quality of 'coherence'. 'Coherence', according to theories of environmental psychology (Kaplan, 1987), is considered a predictor of preference. Locations with these properties may be

preferred because, as the results suggest, they may favour context or place recognition. Representation of place, as opposed to representation of temporal sequences, probably relies or combines different aspects of memory and distinct underlying processes. Processing of place-related spatial information is associated with activation of the right hemisphere (Igloi et al, 2010), which might explain why the observed significant differences are stronger at the right electrodes (Figure 4.3-4; Figure 4.3-8; Figure 4.3-9). Locations with spatial properties that can be described by relatively low values of clustering coefficient and high values of visual control, may serve as spatial cues that contribute to the construction of a ‘map’ (spatial and conceptual) and the emergence of higher-order knowledge structures. The following paragraphs offer some theoretical speculations, in an attempt to explain the results within the context of the relevant theories.

Sensory inputs seem to form the basis for both bottom-up driven egocentric representations as well as spatial imagery and the “explicit recall of spatial configurations of known spaces” (Bicanski & Burgess, 2018). The spatial coding within the entorhinal cortex, retrosplenial complex and the parahippocampal place area<sup>34</sup>, appears to have similarities in both “visually guided reorientation and spatial imagery” (Vass & Epstein, 2017). When subjects orient, based on the immediately perceived visual information or based on imagined viewpoints, their brains elicit the same neural activity patterns. The common neural response might be related to an 'abstract identity code' of visuospatial features that corresponds to the same location, which seems to go beyond memory encoding and perception (Vass & Epstein, 2013). For example, the parahippocampal place area that is associated with location and place recognition, has been reported to 'use' an 'abstract identity code' to represent the same landmark across its different perceptual instantiations (Marchette et al. 2015).

The idea of an 'identity code' is not far from Buzsáki's theories on omnidirectional representations, which explicitly define positions and may symbolize the 'meaning' of an item. High visual control and relatively low clustering coefficient values are often associated with street junctions and are usually found at visually dominant locations with multidirectional visual fields. A possible relation between these isovist

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<sup>34</sup> regions involved in heading, self-localisation and place recognition.

properties and the omnidirectional firing of place cells, which usually occurs at junction location and open fields, is perhaps conceivable. Given the findings from this research, it is not unreasonable to assume that visually dominant locations with multidirectional visual fields may function as 'cue conjunctions' and 'explicit gnostic units' triggering the spatial Aha! moment.

The involvement of the hippocampus has been traditionally associated with aspects of navigation. However, according to the relational theory, the processes related to the functions of the hippocampus are perhaps not only involved in spatial memory but rather support the operations of 'a memory space'. From this perspective, the relationship between episodic learning and the emergence of 'maps' can be related to both spatial and conceptual dimension. Another possible explanation comes from the involvement of hippocampus in "scene construction" which, according to Hassabis (Hassabis, 2009) forms "the basis of imagination and possibly creativity, where constructions are envisaged that are not directly related to the future or the past, or to prediction per se, but for general problem-solving". Interestingly, Hassabis (2009) discusses that when one is confronted by the possibility of several future actions, processes related to 'scene construction', which involve imagining and simulating mentally future experiences in a rich and accurate way, facilitates the evaluation of the desirability of those outcomes and the planning processes. This ability of 'scene construction', therefore, might support spatial re-orientation. In this case, one needs to simulate mentally the possible outcomes of the choices of movement offered at the current location, and thus construct a mental image of the current location in relation to allocentric information (e.g. in the current experiment that would be the knowledge acquired from studying the map).

Hillier's intuition that "spatial relations are ideas we think with rather than of" is probably not far from the ideas discussed in the previous paragraphs (Hillier, 2006). He refers to a higher-level template that allows us to synchronise the discrete spatial objects and experiences for further embodiment. Quite in line with the idea of a higher order representation that is "invariant to the conditions that created it" (Buzsaki, 2005), he suggests that this upper-level recognition (the higher-level template) is most probably not just the "recursion process of locally similar events" but is in some sense "independent of the lower-level constructive process" (Hillier,

2006). Among the several interesting views that he offers, there are two insightful ideas that I think are closely related to the issues discussed here.

The first is that “the process of synchronisation in the upper level of the description retrieval process seems to require certain **formal properties** to be satisfied at that level and will not happen without those properties” (Hillier, 2006, emphasis added). The nature of these ‘formal properties’ and the mechanisms that permit the emergence of the higher-order knowledge from the level of perception of spatial relations (e.g. multidirectional visual scenes), is quite an interesting issue. As discussed in section 2.1.1, the emergence of cognitive meaning seems to have its origins at the level of the perceptual meaning, which according to Pinna (2010) emerges in response to the complexity of the form of shape: “The increasing of complexity from one level to another is accompanied by a strong reduction of the number of contents and by the increasing of simplicity” (Pinna, 2010). The perceptual sentence is built around the notion of “happening” which creates unity. The ‘happening’ explains in a way the lack of homogeneity ('modal partialness') and might trigger an affective response<sup>35</sup> to complex stimuli. Perhaps, such a response to locations with increased environmental complexity might be related to the mechanisms that facilitate the construction of higher-order knowledge.

In addition, Hillier argues that “our mental interaction with the spatial world engages abstract relational ideas as well as concrete elements”<sup>36</sup>, and highlights that we use some kind of embedded rule, an abstract scheme of spatial relations, which is “inherent in the *concrete* behaviour” (Hillier, 2006, emphasis added). Saying “human behaviour is full of embedded rules of this kind” (Hillier, 2006) places these ideas in close relation to Varela’s notions of ‘microidentities’ and ‘microworlds’ (Varela, 1991). Varela argues that from the enactive perspective, the units of knowledge are not abstract but are primarily concrete, embodied, lived (Varela, 1991). The birthplace of the concrete units of knowledge (or common sense) originates during *breakdowns*, that is, during transitions into new modes of behaving.

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<sup>35</sup> associated with the theory of an arousal-reduction mechanism in studies of environmental psychology as mentioned in section 2.3.3

<sup>36</sup> He uses the term ‘description retrieval’ to refer to the mechanism “through which we extract abstract information from concrete events and re-embodiment it in real time” (ibid.)

New modes of behaving, which Varela calls 'microidentities', are possible due to our *readiness-to-action* and correspond to every specific lived situation, to specific 'microworlds' (ibid.). Varela offers the following example to illustrate what it is like being-there, during breakdowns:

How are we to understand the very moment of being-there when something concrete and specific shows up? Picture yourself walking down the street, perhaps going to meet somebody. It is the end of the day and there is nothing very special in your mind. You are in a relaxed mood, in what we may call the readiness of the walker who is simply strolling. You put your hand into your pocket and suddenly you don't find your wallet where it usually is. Breakdown: you stop, your mind setting is unclear, your emotional tonality shifts. Before you know it, a new world emerges: you see clearly that you left your wallet in the store where you just bought cigarettes. Your mood shifts now to one of concern for losing documents and money, your readiness-to-action is now to quickly go back to the store. There is little attention to the surrounding trees and passers-by; all attention is directed to avoiding further delays (Varela, 1991).

Varela emphasizes how the substance for experience is the embodied sensory-motor structure and that the “experiential structures 'motivate' conceptual understanding and rational thought” (Varela, 1991). The cognitive structures emerge from “the kinds of recurrent sensory-motor patterns that enable action to be perceptually guided” (Varela, 1991). Multiple overlapping observations with common junctions lead to the emergence of omnidirectional place cells which are the hallmark of the cognitive map (Buzsaki, 2005). This suggests that the experience of moving through spaces over time is more than just the experiences of those individual spaces.

Locations with multi-directional fields of view (e.g. as described by clustering coefficient), may afford action to be perceptually guided through visual exploration.<sup>37</sup> However, the experience of the 'recurrent sensory-motor patterns' that occurs through multiple overlapping trajectories (Buzsaki, 2005) suggests that there

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<sup>37</sup> the 'visits' of the eye



are probably some relevant factors that this thesis might have missed. This is because the focus has been on the experience of individual spaces rather than the experience of moving through spaces over time. On the other hand, the perspective of ‘scene construction’ that is associated with imagining future experience, perhaps offers an explanation more closely related to the thesis. This view might be more closely related to the experience of individual spaces and the emergence of higher-order structures through episodic recall rather than during encoding, which requires multiple overlapping trajectories (Koster et al, 2018).

The results show that the spatial Aha! experience of spontaneous self-localisation and place recognition has a strong association with the clustering coefficient which describes quantitatively the 'junctionness' or 'spikiness' of the shape of the visibility polygons. “A shape”, according to the new gestalt principles of perceptual organization, “is the starting point of a meaning and a meaning is the meaning of a shape” (Pinna, 2010); therefore, one could assume that the increased complexity of the perceived 'form of shape' at these locations, triggers the emergence of a perceptual meaning that reduces substantially the information load. The 'concrete, embodied and lived' units of spatial knowledge at location with relatively low clustering coefficient and high visual control can be associated with the multi-directional possibility of movement and the promise of new visual information. A change in complexity might be the birthplace of a new 'microworld' – where multiple vectors of movement become possible – and of a new 'microidentity', linked to a change in the course of action. Perhaps, the breakdown that one might experience during the transition into new modes of behaving 'motivates' the birth of concrete units of spatial knowledge. These concrete units of spatial knowledge might belong to a larger collection of spatial cues that give rise to a map-based conceptual structure; or as better described by Buzsáki: “a large collection of cue conjunctions that overlap, with the conjunctions providing a framework for moving among the cues” (Buzsaki, 2005).

## **5.4 Conclusions and Contributions of the Thesis**

The departure point of this thesis is the observation of the analogy between two previously unrelated phenomena and the attempt to provide a theoretical synthesis

between them; that is, between the experience of sudden re-orientation and the spontaneous Aha! moment in insightful problem solving. This analogy is supported by evidence from studies which show that the hippocampal system is not only involved in a cognitive mapping of spatial information but also in memory processes of non-spatial relations. The ‘memory space’ in the hippocampus is associated with the generation and recombination of units of knowledge of the physical and conceptual space.

The literature review of studies on navigation and orientation, on insightful problem solving and on context updating triggered by target stimuli, suggest that there is a similar pattern of cognitive processes underlying these two instances of this phenomenon. These are the shift of attention and encoding of novelty (target stimuli or novel environmental information), the recognition of a target or cue that triggers a change in the representation, the conflict resolution between old and new representations, and the transformation of the information between frames of reference.

Sudden availability of novel visuospatial information that is relevant to the task, will increase working memory demands and activate processes related to the evaluation of the stimulus, usually resulting in increased delta/theta power (Bachman & Bernat, 2018; Jaiswal et al, 2010; Yordanova et al, 2000). According to the literature from different areas of research, the underlying processes that are most likely related to the spatial Aha! experience should be reflected by a frontal/central increase in theta power related with increase task demands (e.g. conflict resolution) and recognition-related decision-making, and a posterior alpha power decrease associated with the translation of spatial information between egocentric and allocentric frames of reference.

It is important to clarify that the data analyses of this thesis are only focused on the first mechanisms that underlie the process of re-orientation, which is the place recognition and re-orientation to a different reference frame, and not on the second sub-process which is heading retrieval. Hence, the time reference point and main event of interest, in both behavioural and EEG analyses, is the change in the course of action (i.e. participants' movement); that is, the moment participants decided to

release the button of forward movement, just before their response. This change in behaviour, perhaps, suggests a transition into a new 'microworld' during which, according to Varela, concrete, embodied and lived units of knowledge emerge (Varela, 1991). The objective here was to assess what the spatial properties of this specific 'microworld' are.

Hence, this enquiry and the rationale of the experimental paradigm used here is not guided by the traditional neuroscientific approaches that answer questions like: 'what is the brain's response?'; but, by the objective to answer a more space-oriented question: *What are the visuospatial conditions that may engender the Aha! moment of re-orientation?* Theories from the field of environmental psychology pointed towards two hypotheses that the Aha! experience could be triggered: (a) by a change in the amount of visual information as described by isovist measures of area and revelation; or (b) by a change in the complexity of the visual information as described by clustering coefficient and visual control. Behavioural (section 4.2) and electrophysiological (section 4.3) results reveal an association between the spatial Aha! moment and the complexity of the visual-spatial environment<sup>38</sup>, as measured by the relevant isovist properties.

In summary, the frontocentral delta/theta power increase is coupled with a sudden large decrease in the values of clustering coefficient within 3s before the event of interest, which suggest that this environmental change is most likely perceived as a cue and triggers processes of re-orientation. Participants tend to stop to give their response at locations with relatively low clustering coefficient and high visual control, and only these two isovist properties show significant differences (response-related) between trials that exhibit the expected brain dynamics and trials that do not. Therefore, a change in participants' behaviour and brain dynamics is coupled with a change in the environmental context. The recognition of informationally-relevant novelty (change in the complexity) seems to facilitate the re-orientation to a new frame of reference and engenders the emergence of a 'bisociative' relation between

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<sup>38</sup> It is possible, as discussed in section 5.1, that a sequence of events (a change in the amount followed by a change in complexity of the visual information) is what might trigger this experience but the findings here do not support this alternative hypothesis.

the new and the old representation which gives rise to a new third hinge-dimension of experience: the Aha! moment.

The thesis employs a methodology that combines techniques and analytic methods from two distinct disciplines. One of the main contributions of this thesis is the introduction of the EEG methodology within the research field of the built environment, which offers an opportunity to record and study brain activity and individual spatial behaviour in relation to quantitative spatial properties (isovist). The objective was to design an experimental paradigm and develop a methodological approach that takes into consideration the 'link' between experiential events and mental events (neural firings) alongside a synchronised context-based quantitative analysis. This approach takes into account the enactive perspective to cognition and considers the synchronous investigation of these three aspects important for a better understanding of the 'structural coupling' of the living being and its environment. Environmental modelling techniques such as space syntax and visibility graph analysis offer a quantitative tool that can form the basis of the context-based analysis.

Within the space syntax community it seems to remain still relatively unclear whether the correlations between aggregate flows of movement and syntactic variables “are due to cognitive factors operating at the level of individual movers, or they are simply mathematically probable network effects [...] independent of the psychology of navigational choices” (Hillier & Iida, 2005). Montello's discussion about the contribution of space syntax to environmental psychology includes this observation, and he comments on how space syntax methodology falls short in taking into consideration differences in people's responses to layouts (Montello, 2007). The key findings of this experimental paradigm respond to these critical accounts and provide evidence of the strong relation between isovist measures and the cognitive factor at the level of the individual. The contribution of this thesis is to provide empirical evidence of how spatial properties affect individual human spatial experience, cognition and behaviour and trigger different patterns of neural activity. The results and methodology used in this paradigm open new directions for further research. They provide the ground upon which new hypotheses can be structured,

and the means to control experimental conditions, based on quantitative environmental modelling, in innovative virtual reality neurophysiological studies.

The research has demonstrated a link between the spatial context and mental events, an external and internal dimension of the Aha! moment, an experience otherwise familiar only anecdotally, as in the following quote:

Emerging from the platform [of London underground] to the streets of an unknown station. First came confusion. Not recognising where I was, not finding anything that I could relate to as known space. Then came anguish, a space that shrank and expanded at the same time, just for a few seconds, before recognising that I was lost. Then a rush of adrenaline to the head that kicked in a feeling, a need, for action that made me look for alternatives to find a path forward. Then came relief, when finding the first 'colour/light' of something known, which made me ground myself and allowed me to walk forward...It was like a discovery! (Mara Torres Pinedo, 2018)

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